# ANNUAL RESEARCH REPORT
# U.S. WATER CONSERVATION LABORATORY

## 1995



USDA - AGRICULTURAL RESEARCH SERVICE
Phoenix, Arizona

# ANNUAL RESEARCH REPORT

**1995**

U.S. WATER CONSERVATION LABORATORY
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## INTRODUCTION

The U. S. Water Conservation Laboratory (USWCL) Annual Research Report is intended to describe progress on our research projects in 1995 and plans for 1996 and beyond. Our targeted reading audience includes upper level management within the Agricultural Research Service, other ARS research locations and entities involved in natural resources research, and our many collaborators and cooperators. It is our intent to keep the individual reports short but informative, focusing on what is being done and why, the problem, objectives, approach, brief results, future plans, and cooperators involved in each program. We want to make sure that the product of the research and its contribution to water conservation are clear to all.

This year we have intensified our efforts to identify our clients, inform them of our research, and benefit from their insights. The identification process started in February, after our 1995 Annual Research Program Review and Planning meeting. In October, as part of our Annual Science and Engineering Open House, targeting science students from local high schools, we held a special open house for farmers, the media, state legislators, staff of the Arizona congressional delegation, representatives of Arizona state agencies, irrigation districts, private enterprise, and the general public. About 50 attended. The 1996 Annual Research Program Review and Planning meeting will be a continuation of the effort, in which we will host a broad cross-section of persons interested in our research program. These types of activities, along with the Annual Research Report, all provide opportunities for us to tell our research story and to assess and make our program more responsive to identified needs.

Additional permanent funding was directed to the USWCL in 1994 to increase research on the application of technology, part of which is to focus on the utilization of remotely sensed data to aid farm management. Mr. Edward M. Barnes, Agricultural Engineer, joined the staff and the Remote Sensing Group in September 1995 to lead the program in the stated area. Along with developing his program, he is feverishly working on completing his Ph.D. dissertation. Mr. Brian T. Wahlin, Civil Engineer, was hired as a permanent Category 3 researcher in the Irrigation Group. He will be working mainly in water measurement. Dr. James J. Toth, Meteorologist, in a shared assignment between the Remote Sensing Group of the U. S. Water Conservation Laboratory and the Southwest Watershed Research Unit in Tucson, joined the staff as a post-doctoral research associate. Dr. Toth, on a two-year appointment, is developing a combined remote sensing/modeling tool for investigation of meteorological processes on a regional scale. Near year's end, an Administrator's post-doctoral research associate fellowship was awarded to Dr. Gary W. Wall in the $CO_2$-Climate Change Group to study the effects of elevated $CO_2$ and low soil nitrogen on photosynthetic proteins. Recruitment of suitable candidates is underway. I'm pleased to report that Doug Hunsaker in the Irrigation Group completed his Ph.D. from the University of Arizona during the fall of 1995. Congratulations to Dr. Hunsaker. Several existing vacancies for permanent technician positions were filled during 1995. Also, two new technician positions were created and filled in 1995, one each for irrigation and water quality.

As a policy, we strive to leverage our available base funding into well-targeted, broader-based programs by attracting outside resources. We are committed to working collaboratively with other agencies and industry in bringing post doctorates, visiting scientists and engineers, graduate students, and persons on sabbaticals to the USWCL to maintain or expand our research programs.

Outside resources are instrumental in our continued work in major program areas. In-kind human resources provided by many of our cooperators and collaborators are highly significant and enhance our programs, especially by each individual's stimulating effects on our research efforts (please refer to the list of Cooperators shown at the end of each report and summarized on pages viii through x). A number of organizations contributed significant financial support to the USWCL during 1995 as follows: The Irrigation Group received a third year of funding through the USDA Office for International Cooperation and Development, that concluded a three-year collaborative study with the National Agricultural Research Project (NARP) in Egypt dealing with the effects of land leveling precision and tillage practices on surface irrigation performance; and through the Arizona Department of Water Resources, Phoenix Active Management Area, that contributed to a study to develop software for improving the design and management of sloping border irrigation systems. During 1995, after several years of Interagency Cooperation, the Department of Energy stopped direct support of the $CO_2$-Climate Change Group program to evaluate the interactive effects of elevated $CO_2$ and increased temperature on plant growth and physiological processes, including the development of predictive models. On the positive

however, the University of Arizona was awarded a two-year grant by the Department of Defense to continue the FACE (free-air $CO_2$ enrichment) Project studying the interactive effects of elevated $CO_2$ and low soil nitrogen on wheat growth, soil nitrogen processes, and soil carbon sequestration. USWCL personnel continue to be major collaborators to the project, including the day-to-day management. Additionally, temporary ARS Global Change funds were awarded to the group to help support the photosynthetic measurement aspects of the FACE project. The New Crops Group received support through the USDA Alternative Agricultural Research and Commercialization Center for commercialization of Lesquerella; the Department of Defense and the USDA/CSRS Office of Agricultural Materials for two programs (jointly supported): one, a two-year program to accelerate commercialization of vernonia, and the other to expand work on the extraction, characterization, and fabrication of guayule latex products for nonallergenic applications; the USDA-ARS National Germplasm Laboratory (partial support) for the collection of Lesquerella germplasm; and the ARS-National Program Staff, through the Crop Germplasm Committee, for germplasm evaluation. The Remote Sensing Group received funding from the Electrical Power Research Institute to hire Dr. Toth through an ARS Cooperative Research and Development Agreement; from the Japanese Government for exchanges of scientists from the USWCL and the National Institute for Agricultural and Environmental Studies dealing with agricultural remote sensing; and from NASA for students and travel during 1995 for research in hydrologic applications of remote sensing. To the USWCL overall, this outside funding represents about 11% of our total budget, but it amounts to 45 to 50% of our discretionary dollars. We thank these many cooperators/collaborators and will continue working to make these associations mutually beneficial in serving agriculture.

I invite you to read and use this Annual Research Report. Let us know if there are questions or comments, either from a technical research standpoint or about ideas you might have regarding communication with our clients; all are invited and will be appreciated.

Allen R. Dedrick, Director

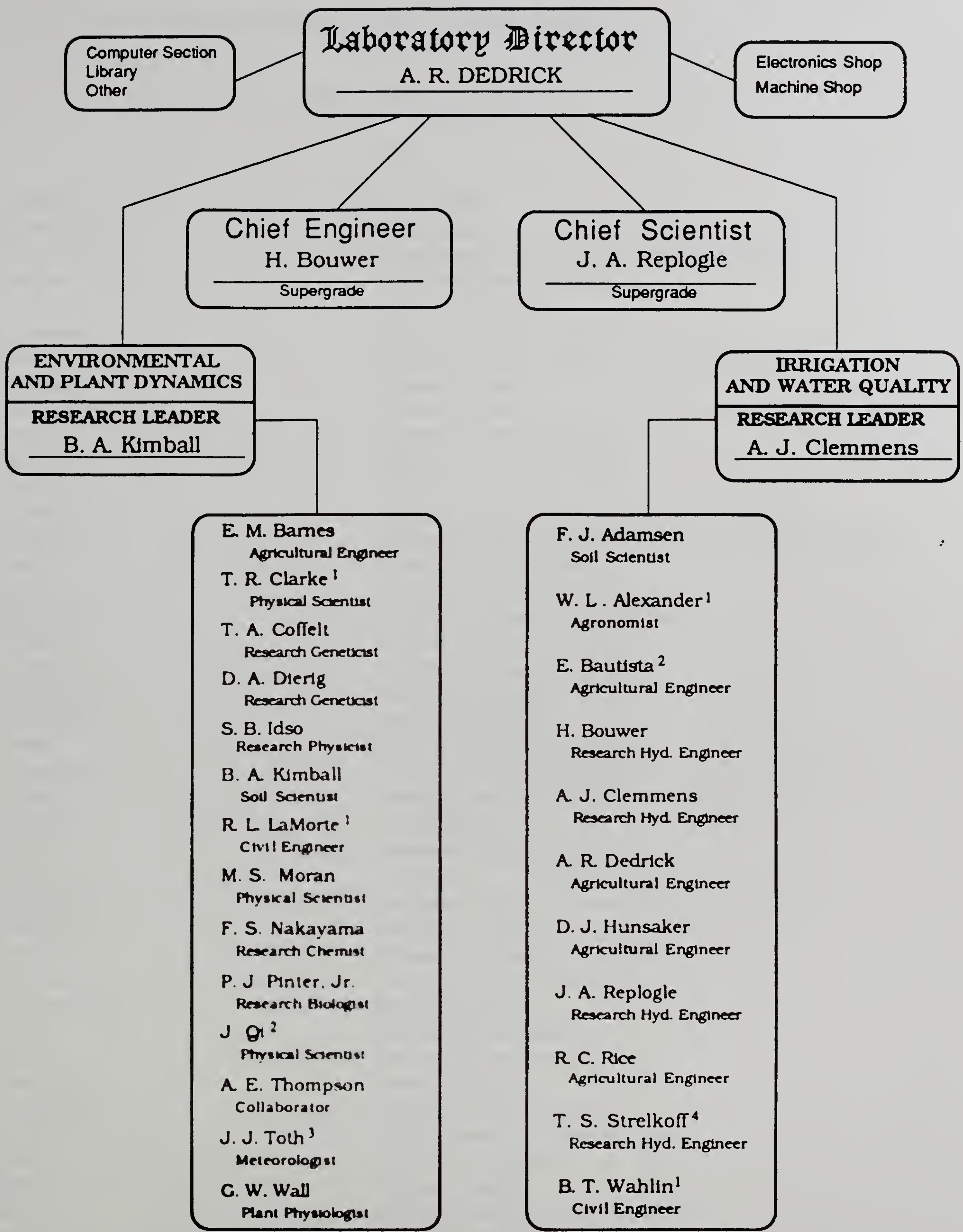
## U. S. WATER CONSERVATION LABORATORY
## ORGANIZATIONAL DESCRIPTION AND MISSION STATEMENTS

The mission of the U. S. Water Conservation Laboratory (USWCL) is to conserve water and protect water quality in systems involving soil, aquifers, plants, and the atmosphere. Research thrusts involve developing more efficient irrigation systems, improving the management of irrigation systems, developing better methods for scheduling irrigations, developing the use of remote sensing techniques and technology, protecting groundwater from agricultural chemicals, commercializing new industrial crops, and predicting the effect of future increases of atmospheric $CO_2$ on climate and yields and water requirements of agricultural crops.

The U. S. Water Conservation Laboratory research program is organized under two Research Units: Irrigation and Water Quality (I&WQ) and Environmental and Plant Dynamics (E&PD). I&WQ focuses on water management with emphasis on irrigation and water quality; E&PD concentrates on carbon dioxide-climate change, germplasm development for new crops, and remote sensing. Drs. Albert J. Clemmens and Bruce A. Kimball are the Research Leaders for the respective Research Units. The organizational structure for the USWCL is shown in figure 1, and the entire USWCL personnel list in table 1.

The mission of the Irrigation and Water Quality Research Unit is to resolve water management problems for irrigated agriculture through research aimed at conserving and augmenting water supplies. Goals are to develop management strategies and tools for the effective use of water and fertilizers in irrigated agriculture, develop tools for the protection of groundwater supplies from degradation as the result of agricultural practices, develop technologies for safe reuse of municipal wastewater, and transfer these results to practice through technology transfer efforts. The unit focuses on identifying individual actions and practices for resolving water supply and quality issues at the farm and project levels, and the various inherent interrelationships.

The mission of the Environmental and Plant Dynamics Research Unit is to develop optimum resource management strategies for meeting national agricultural product requirements within the context of global change. Goals are to predict increased $CO_2$ and global climate change effects on plant growth and water use; develop new crops to meet national needs for renewable, agriculturally-based products; develop remote sensing techniques for farm management and wide-area evapotranspiration estimation. $CO_2$-climate research will furnish a knowledge base and models to assess global change impact on future agriculture, increasing the security of the world's food supply and benefitting all consumers. New Crops will diversify American Agriculture while producing renewable sources of raw materials such as non-allergenic latex (medical products), hydroxy fatty acids (cosmetics and lubricants), and low pollutant epoxy fatty acids (paints and coatings). Remote Sensing research will benefit growers and consumers by improving farm management decisions and the accuracy of water resource assessments.




[1] Category 3 scientist
[2] Post-Doctoral Research Associate
[3] Post-Doctoral Research Associate (shared 50%/50% by US Water Cons. Lab., Phoenix, and Southwest Watershed Research, Tucson.)
[4] Research Professor, University of Arizona

Figure 1. U. S. Water Conservation Laboratory Organization, December 31, 1995

Table 1. U. S. Water Conservation Laboratory Staff, December 31, 1995

PERMANENT EMPLOYEES

| Name | Title |
|---|---|
| Adamsen, Floyd J. | Soil Scientist |
| Alexander, William L. | Agronomist |
| Arterberry, Carl A. | Agricultural Science Research Technician/Soils |
| Askins, JoAnne | Physical Science Technician |
| Barnes, Ed | Agricultural Engineer |
| Bouwer, Herman | Research Hydraulic Engineer |
| Brown, Rita | Agriculture Science Research Technician/Plants |
| Clarke, Thomas R. | Physical Scientist |
| Clemmens, Albert J. | Research Leader and Supervisory Research Hydraulic Engineer |
| Coffelt, Terry A. | Research Geneticist (Plants) |
| Colbert, Sharette | Physical Science Technician |
| Corris, Virginia D. | Office Automation Assistant |
| Dahlquist, Gail H. | Agricultural Science Research Technician/Plants |
| Dedrick, Allen R. | Laboratory Director and Supervisory Agricultural Engineer |
| Dierig, David A. | Research Geneticist (Plants) |
| Gerard, Robert J. | Laboratory Support Worker |
| Gerszewski, Susette | Biological Science Technician/Plants |
| Harner, Paulina A. | Secretary (Office Automation) |
| Heckart, Donna J. | Secretary (Office Automation) |
| Hunsaker, Douglas J. | Agricultural Engineer |
| Idso, Sherwood B. | Research Physicist |
| Johnson, Kathy | Physical Science Technician |
| Johnson, Stephanie M. | Biological Science Technician |
| Kimball, Bruce A. | Research Leader and Supervisory Soil Scientist |
| LaMorte, Robert L. | Civil Engineer |
| Lee, Richard | Custodial Worker-Admin |
| Lewis, Clarence L. | Machinist |
| Martinez, Juan M. R. | Agricultural Science Research Technician/Soils |
| Mastin, Harold L. | Computer Assistant |
| Mills, Terry A. | Computer Programmer Specialist |
| Moran, M. Susan | Research Physical Scientist |
| Nakayama, Francis S. | Research Chemist |
| Padilla, John | Engineering Technician |
| Pettit, Dean E. | Electronics Engineer |
| Pinter, Paul J., Jr. | Research Biologist |
| Powers, Donald E. | Physical Science Technician |
| Replogle, John A. | Chief Research Hydraulic Engineer |
| Rice, Robert C. | Agricultural Engineer |
| Rish, Shirley A. | Program Analyst |
| Rokey, Ric | Biological Science Technician/Plants |
| Salisbury, T. Lou | Secretary (Office Automation) |
| Seay, L. Susan | Publications Clerk (Office Automation) |
| Seay, Ronald S. | Agricultural Science Research Technician |
| Strand, Robert | Engineering Technician |
| Vinyard, Stephen | Physical Science Technician |
| Wahlin, Brian | Civil Engineer |
| Wall, Gerard W. | Plant Physiologist |

## TEMPORARY EMPLOYEES

| Name | Title |
|---|---|
| Bautista, Eduardo | Agricultural Engineer |
| Bhattacharya, N. | Collaborator |
| Do, Phong | Computer Programmer Assistant (resigned 1/12/95) |
| Fritz, Kent I. | Physical Science Aid |
| Gardner, Bruce | Office Automation Clerk-Admin |
| Gulbranson, Scott | Biological Science Technician (resigned 3/08/95) |
| Johnson, David | Engineering Technician (resigned 5/18/95) |
| Kaiser, Aaron | Biological Science Aid |
| Kuramoto, Jane | Physical Science Aid (resigned 2/10/95) |
| Lauver, Lisa | Biological Science Aid |
| Mitchell, Tom | Engineering Technician |
| Olivieri, Laura | Biological Science Technician |
| Perry, Ed | Biological Science Technician (resigned 6/25/95) |
| Price, Gavin | Engineering Aid (resigned 1/13/95) |
| Pottenger, Christine | Biological Science Lab Technician (resigned 8/11/95) |
| Qi, Jiaguo | Physical Scientist |
| Rebman, Jon | Biological Science Technician/Plants |
| Renteria, Francisca | Custodial Worker |
| Richards, Stacy | Biological Science Aid |
| Slosky, Edward | Engineering Technician |
| Thompson, Anson | Collaborator |
| Tomasi, Belinda | Physical Science Technician |
| West, Kathy | Biological Science Technician |
| Yanas, Ruben | Computer Programmer Assistant (resigned 6/09/95) |

## TEMPORARY STATE EMPLOYEES

| | |
|---|---|
| Baker, Michael | Research Specialist-Staff |
| Brooks, Talbot | Research Technician |
| Freitag, Laurie | General Maintenance Mechanic/Staff |
| Leake, Gregory | Research Technician-Staff |
| McCurdy, Charles | General Maintenance Mechanic |
| Novak, Patricia | Research Assistant/FACE |
| O'brien, Carrie | Research Lab Assistant-Staff |
| Olivieri, Jose | Computer Programmer Assistant (resigned 4-23-95) |
| Pabian, David | Associate Eng/FACE |
| Schmidt, Baron V. | Computer Programmer Asst |
| Tomasi, Pernell | Research Lab Assistant |

## U. S. WATER CONSERVATION LABORATORY
## COOPERATORS for 1995

| INSTITUTION | CITY/COUNTRY/STATE |
|---|---|
| **Universities** | |
| Arizona State University | Tempe, Arizona |
| California Polytechnic State University | San Luis Obispo, California |
| California State University | Fresno, California |
| Colorado State University | Fort Collins, Colorado |
| Delft Technical University | Delft, The Netherlands |
| Free University of Amsterdam | The Netherlands |
| Humbolt University | Berlin, Germany |
| Kansas State University | Manhattan, Kansas |
| Moshtohor Zagazig University | |
| Dept of Crops & Agricultural Engineering | Cairo, Egypt |
| Oregon State University | Corvallis/Medford, Oregon |
| Rutgers University | New Brunswick, New Jersey |
| Texas A&M University | Fort Stockton/College Station, Texas |
| Virginia State University | Petersburg, Virginia |
| University of Akron, Department of Polymer Science | Akron, Ohio |
| University of Alberta | Edmonton, Alberta, Canada |
| University of Arizona | Tucson, Arizona |
| College of Agriculture | |
| Cooperative Extension | |
| Dept of Plant Sciences | |
| Dept of Soil & Water Science | |
| Dept of Hydrology & Water Science | |
| Dept of Agric & Biosystems Engineering | |
| Office of Arid Land Studies | |
| Maricopa Agricultural Center | Maricopa, Arizona |
| Universitat Autonoma | Barcelona, Spain |
| Universita della Tuscia | Viterbo, Italy |
| Department of Biochemistry & Agrochemistry | |
| University of Essex | Colchester, United Kingdom |
| University of Florida | Gainesville, Florida |
| University of Georgia | Athens, Georgia |
| University of Guelph | Guelph, Ontario, Canada |
| University of Idaho | Moscow, Idaho |
| University of Kentucky | Lexington, Kentucky |
| University of North Dakota | Fargo, North Dakota |
| University of Wisconsin | Madison, Wisconsin |
| University of Michigan | Ann Arbor, Michigan |
| Utah State University | Logan, Utah |
| Dept. of Biological & Irrigation Engineering | |
| **Federal Agencies** | |
| Consolidated Farm Service Agency | Casa Grande, Arizona |
| Lawrence Livermore National Laboratory | Livermore, California |
| Sandia National Laboratories | Albuquerque, New Mexico |

| | |
|---|---|
| U. S. Bureau of Reclamation | |
| Water Resources Research Laboratory | Denver, Colorado |
| Lower Colorado Region | Boulder City, Nevada |
| Phoenix Area Office | Phoenix, Arizona |
| USDA, Natural Resources Conservation Service | Phoenix/Casa Grande, Arizona |
| USDA-ARS, Grassland Protection Research | Temple, Texas |
| Hydrology Laboratory | Beltsville, Maryland |
| National Center for Agricultural Utilization Research | Peoria, Illinois |
| National Soil Dynamics Laboratory | Auburn, Alabama |
| Western Regional Research Center | Albany, California |
| Russell Research Center | Athens, Georgia |
| Soil & Plant Research | Fort Collins, Colorado |
| Southwest Watershed Research Center | Tucson, Arizona |
| Tropical Crops & Germplasm Research | Mayaguez, Puerto Rico |
| U.S. Salinity Laboratory | Riverside, California |
| Western Cotton Research Laboratory | Phoenix, Arizona |
| Western Wheat Quality Laboratory | Pullman, Washington |
| USDA-CSREES | Washington, DC |
| U.S. Department of Energy | Washington, DC |
| Atmospheric & Climate Research Division | |
| Office of Health and Environmental Research | |
| USDA-FS, Rocky Mountain Forest & Range Experiment Station | Fort Collins, Colorado |

State Agencies

| | |
|---|---|
| Arizona Department of Agriculture | Phoenix, Arizona |
| Arizona Department of Environmental Quality | Phoenix/Tucson, Arizona |
| Arizona Department of Water Resources | Phoenix, Arizona |
| Phoenix Active Management Area | Phoenix, Arizona |
| Pinal Active Management Area | Casa Grande, Arizona |
| Irrigation Management Service | Casa Grande, Arizona |
| West Pinal Natural Resource Conservation District | Casa Grande, Arizona |

Other

| | |
|---|---|
| Agrigenetics | Madison, Wisconsin |
| Agropecuaria El Valle | Argentina |
| Armtec, Inc. | Lethbridge, Canada |
| Automata, Inc. | Grass Valley, California |
| Brookhaven National Laboratory | Upton, Long Island, New York |
| Buckeye-Roosevelt Natural Resources Conservation District | Buckeye, Arizona |
| Center for Irrigation Technology | Fresno, California |
| Central Arizona Irrigation & Drainage District | Eloy, Arizona |
| Central Arizona Water Conservation District | Phoenix, Arizona |
| Coachella Valley Resource Conservation District | Indio, California |
| Electric Power Research Institute | Palo Alto, California |
| Gila River Farms | Pinal County, Arizona |
| CESBIO, CNES | France |
| GERSAR-SCP, Societedu Canal du Provence | Aix-en Provence, France |
| Global Water | Fair Oaks, California |
| Goddard Space Flight Center, NASA | Greenbelt, Maryland |
| Groenestein en Borst vof | The Netherlands |
| CEMAGREF-ENGREF Remote Sensing Lab | Montpellier, France |

| | |
|---|---|
| CEMAGREF-Irrigation Division | Montpellier, France |
| Imperial Irrigation & Drainage District | Imperial, California |
| Institute of Environmental Analysis & Remote Sensing for Agric | Florence, Italy |
| International Institute for Land Reclamation and Improvement | Wageningen, The Netherlands |
| Irrigation Association | Fairfax, Virginia |
| Maricopa Stanfield Irrigation & Drainage District | Stanfield, Arizona |
| Mexican Institute of Water Technology | Cuernavaca, Mexico |
| National Institute of Agro-Environmental Sciences | Tsukuba, Japan |
| Potsdam Institute for Climate Impact Research | Potsdam, Germany |
| Salt River Project | Phoenix, Arizona |
| Wellton-Mohawk Irrigation & Drainage District | Wellton, Arizona |

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APPENDIX B
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# INTEGRATED IRRIGATION SYSTEM WATER MANAGEMENT

# MANAGEMENT IMPROVEMENT PROGRAM (MIP) FOR IRRIGATED AGRICULTURE

A.R. Dedrick, Supervisory Agricultural Engineer; E. Bautista, Agricultural Engineer;
S.A. Rish, Program Analyst; and A.J. Clemmens, Supervisory Research Hydraulic Engineer

**PROBLEM:** Enhanced long-term management of water and other natural resources, grower profitability, and overall social well-being are essential to a sustainable irrigated agriculture. Because approaches to these objectives are often uncoordinated, all agricultural stakeholders—farmers, irrigation districts, other support and regulatory organizations, and other interested parties—need to interact proactively to address these needs. To this end, the Management Improvement Program (see figure 1 for an elaboration of the three-phased MIP process), a management process similar to those used to improve the performance of corporate organizations, was applied to the business of irrigated agriculture. The purposes of this research are 1) to develop, apply, and refine for future use the MIP methodology; and 2) to establish conditions in the MIP application area for the continued improvement of farming practices and support services provided to farms by district and other irrigation related agencies while conserving related resources.

**APPROACH:** In December 1990, under the direction of the U. S. Water Conservation Laboratory, an Interagency Management Improvement Program (IMIP) was initiated by seven agencies[1] interested in the potential of the MIP to support improved irrigated agricultural productivity, profitability, and natural resource management. From April 1991 to January 1994, a demonstration project was carried out in the Maricopa-Stanfield Irrigation and Drainage District (MSIDD) in central Arizona (see figure 2 for a schematic representation of participating entities). In January 1994, the MIP Team[2] ended its formal leadership of the Demonstration MIP, and the local, grower-led, grower-interagency MSIDD MIP Coordinating Group assumed ongoing responsibility to initiate and guide future MIP initiatives in the MSIDD area. A formal evaluation of the MSIDD-Area MIP was completed and the report published in October 1994. Following are key events and activities in the IMIP and the MSIDD-Area MIP during 1995 (see "Annual Research Reports," 1991 through 1994, for milestones during those years):

1) IMIP Coordinating Group Review (2/95). The MIP Team convened a meeting of the IMIP Coordinating Group to review the current status of the IMIP effort, focusing on the Demonstration MIP and exploring what lay ahead for the IMIP and the role they might continue to play. Included in the agenda was a joint meeting with the MSIDD-MIP Coordinating Group to provide an opportunity for an exchange between the two groups on their respective areas of interest.

2) Exploration of Potential Reapplications of the MIP (ongoing).

a) A Texas irrigation district has requested that the MIP Team explore with them the feasibility of an MIP application to frame and support their long-term improvement plans. The district's request that an MIP be explored as a means of addressing needs they have identified satisfies a main criterion for a next MIP site, that of a need specified by stakeholders. Further, the Texas district offers sharp contrasts to MSIDD, which would further test the MIP process. In May 1995, members of the board, management, district consultants, and an NRCS representative visited USWCL and the MSIDD area and discussed the Demonstration MIP with the MIP Team and MSIDD-area grower and agency MIP participants. In June 1995, members of the MIP Team made an invited visit to the irrigation district to tour the area and continue discussions. The visit included a presentation on the MSIDD-Area MIP to district farmers and other key stakeholders. Discussions are currently underway on plans for the feasibility exploration.

b) In April 1995, at the request of the ARS Office of International Research Programs, the MIP Team submitted a preliminary Work Plan for carrying out an MIP in the Aral Sea area in Uzbekistan. The work plan calls for the

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[1] These agencies, which comprise the general oversight IMIP Coordinating Group, are USDA-ARS and NRCS; USDI-USBR; Arizona Departments of Agriculture, Water Resources, and Environmental Quality; and The University of Arizona Cooperative Extension and College of Agriculture.

[2] The demonstration project MIP Team included Dedrick, Bautista, and Rish of the USWCL; and consultants W. Clyma (MIP Specialist) and D. B. Levine (Management/Team-Building Specialist). The MIP Team provided overall management of the demonstration activities, which included the direct development and facilitation of MIP events. In addition, the Team maintained ongoing communication with participants, addressed concerns and problems as they arose, and was responsible for the development and publication of MIP-related documents.

application to be carried out by local teams; with training, guidance, and project oversight provided by the USWCL-led MIP Team. Approval rests with the U. S. Department of State, which would also provide funding. In late FY 95, the State Department postponed action on the proposal until sometime in FY 96.

3) Consultation with MSIDD-MIP Coordinating Group (10/95 continuing into 1996). Members of the MIP Team were invited to participate in meetings and discussions concerning leadership selection and transition as the first grower-leader's term nears completion. In November 1995, a new grower-leader was confirmed who is scheduled to assume leadership in February 1996. It was also agreed that the MIP Team would structure and lead a special program review and planning meeting of the Coordinating Group in February 1996, coinciding with the leadership transition.

FINDINGS: At their February 1995 meeting, the IMIP Coordinating Group committed to continued involvement in the IMIP and considered how they might play an expanded role in publicity and marketing activities. Grower and agency participants in the MSIDD-MIP continued to affirm the value of the MIP's collaborative, interagency approach to improve the sustainability of irrigated agriculture through their continued support of and participation in the MSIDD-MIP Coordinating Group and its programs and spin-off activities. Now moving into its third year, the MIP Coordinating Group continues to sponsor town-halls, including a grower-requested forum that resulted in formation of a pest-control district, and to publish a newsletter. Grower-to-grower meetings are continuing, and attendance is increasing. A new program initiated this year aims to assist new growers by convening meetings of agriculture-related organizations and other growers to share pooled knowledge and information. These meetings, like the grower-to-grower meetings, have expanded beyond the MSIDD area. One of the most consistent messages from agency participants continues to be the value of the Diagnostic Analysis (DA) and the need to address the numerous opportunities for improvement identified in the DA Report that still remain.

MSIDD-Area MIP participants are a valuable source of insights and information about the MIP experience—its value and benefits and its demands on time and effort—through meetings, presentations, and other interactions with interested parties. Events this past year included presentations to a World Bank policy and program group, the board and management of a visiting irrigation district, and a meeting of the Arizona Hydrological Society. Some participants are also co-authoring papers documenting the demonstration project.

INTERPRETATION: Continued impact of the Demonstration MIP in the MSIDD area rests largely with the MSIDD MIP Coordinating Group's continued institutional development and initiation and oversight of interorganizational programs. They acknowledge the challenges they face related to demands on members' time, personnel changes affecting individual membership and organizational mandating, identification and recruitment of Coordinating Group leadership, and financial and other support resourcing. At the same time, they continue to show accomplishment. Their request for the MIP Team to lead a program review and planning meeting early next year demonstrates their serious commitment to their unique role in providing a focused, coordinated means to address the needs of the area's irrigated agriculture.

Both the MIP Team and the Texas irrigation district are benefitting from the feasibility exploration activities. The exploratory efforts are providing an opportunity for the MIP Team to consider the usefulness of recommendations relating to pre-MIP activities that were formulated as part of the Demonstration MIP Evaluation Report. For their part, District representatives have had an opportunity to interact with both grower and agency MSIDD MIP participants and thus hear about and observe some of the impacts that can result from an MIP process.

FUTURE PLANS: Work will focus on 1) publications documenting the Demonstration MIP, including a series of manuscripts for a special issue of *Irrigation and Drainage Systems Journal*; five papers and presentations for the proceedings of and a session at the ASCE North American Water and Environment Congress '96, June 1996; and a manual to guide future MIP applications; and 2) exploration of appropriate reapplication of the MIP model, including continuing to explore the freasibility of an application in the irrigation district in Texas. As noted in "Approach," above, the principal criterion for future use of the process will be the need to address a need or needs identified by local stakeholders. Leadership of the next application is seen as transitional, from USWCL in a hands-on role to one of training and guidance. Appropriate institutionalization of the refined MIP methodology outside of ARS will continue to be explored.

COOPERATORS: Cooperators include entities listed in figure 2, plus Colorado State University. Funding has been provided by ARS, USBR, NRCS, and ADWR; with significant in-kind contributions by all involved.

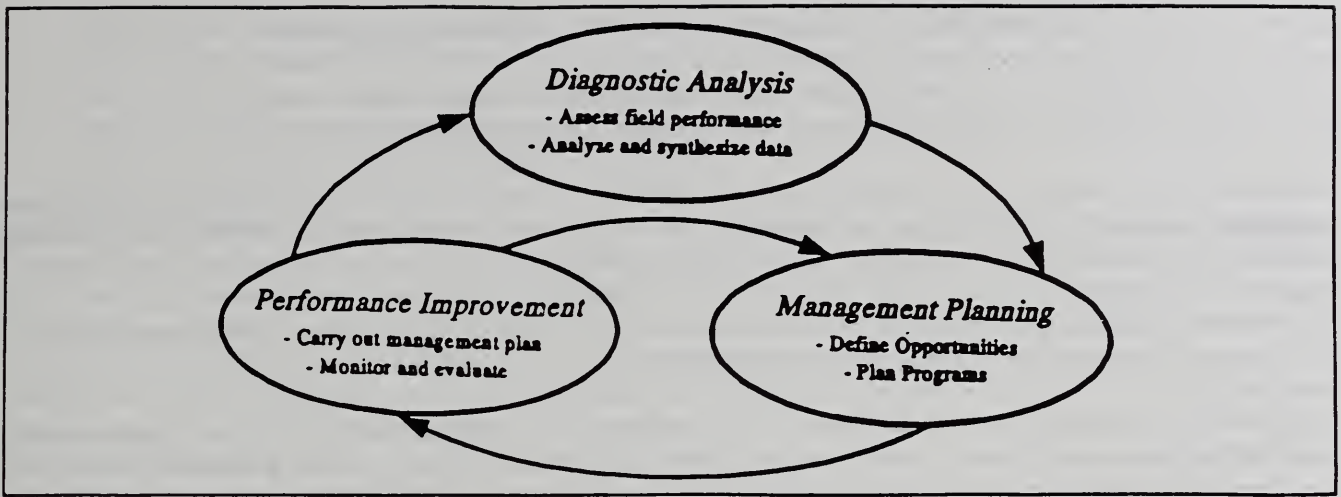
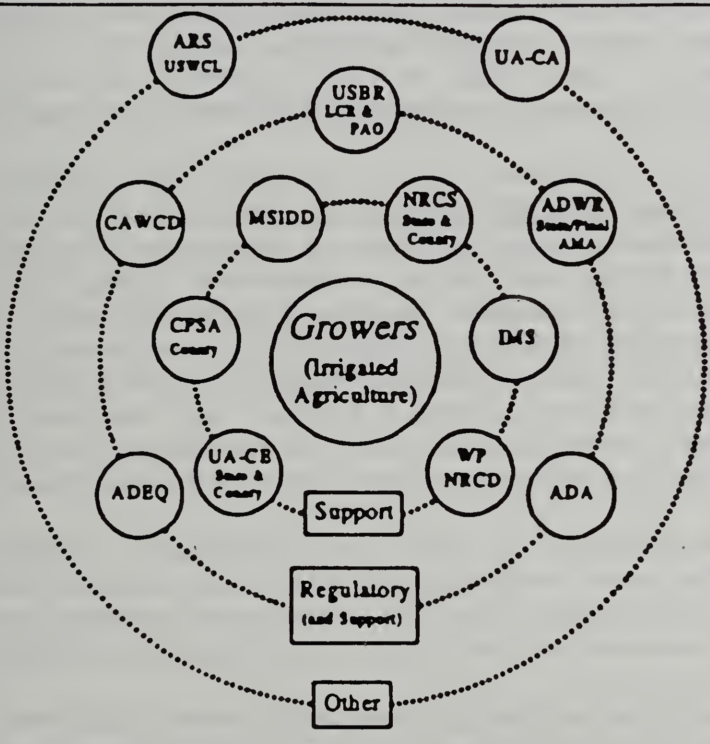



Figure 1. The three phases of the Management Improvement Program feed into one another. Diagnostic Analysis yields an interdisciplinary understanding of the performance of irrigated agriculture in the area. Management Planning results in a shared understanding of the performance among growers and participating organizations as well as identification of opportunities for improvement and jointly developed plans for managerial and technological changes to address those opportunities. Performance Improvement results in implementation of the plans and establishment of long-term, self-supporting mechanisms to sustain the effort after the formal end of the MIP.




ADA - Arizona Department of Agriculture
ADEQ - Arizona Department of Environmental Quality
ADWR - Arizona Department of Water Resources
AMA - Active Management Area
ARS - Agricultural Research Service, U. S. Water Conservation Laboratory
CFSA - Consolidated Farm Service Agency
CAWCD - Central Arizona Water Conservation District
IMS - Irrigation Management Service
MSIDD - Maricopa-Stanfield Irrigation & Drainage District
NRCS - Natural Resource Conservation Service
UA-CA - University of Arizona College of Agriculture
UA-CE - University of Arizona Cooperative Extension
USBR - U. S. Bureau of Reclamation
LCR - Lower Colorado Region
PAO - Phoenix Area Office
WPNRCD - West Pinal Natural Resource Conservation District

Figure 2. Schematic representation of entities involved in irrigated agriculture in the MSIDD-Area. Entities were included as participants because of their potential to impact irrigated agriculture in the area. Improved profitability and sustainability of irrigated agriculture (along with improved natural resource management) were the goals of the Demonstration MIP; therefore, growers, the main focus of the program, are shown appropriately in the center. Moving outward from the growers, the first circle connects organizations or entities directly supporting agriculture in the MSIDD area; the second connects organizations with primarily regulatory missions although they may also have some support functions; and the furthest circle includes the two research and/or educational organizations involved.

## IRRIGATION INDUSTRY/ARS COLLABORATIVE EFFORT[1]

A.R. Dedrick, Supervisory Agricultural Engineer; and
D. F. Heermann, Supervisory Agricultural Engineer

**PROBLEM:** The "Irrigation Industry/ARS Collaborative Effort," was initiated in 1991, led by Dedrick and Heermann, to promote a concerted, sustained effort to impact irrigation on a broad scale up through the national level. It aimed to address issues facing irrigation as a whole, with its stated purpose,

> "for the Irrigation Industry and the Agricultural Research Service to foster and focus an ongoing partnership in support of irrigation that yields optimal societal benefit,"

**APPROACH:** In May 1991, a workshop with over 40 attendees, almost evenly divided between the Irrigation Industry and ARS irrigation and drainage researchers, met to launch the effort. At that meeting, a Leadership Group was mandated to lead the Collaborative Effort. Over the last four-and-a-half years, the Leadership Group has guided actions to address the agenda that emerged from the workshop, including meetings to adjust overall Collaborative Effort plans and to review and support its work group activities focused on three main thrusts:

- Supporting the Irrigation Association (IA) as a key representative of the Irrigation Industry in identifying priority irrigation related research needs and communicating them to the research community,
- Increasing the amount of collaborative research carried out by Irrigation Industry and ARS scientists and engineers, and
- Proposing and supporting a study by the Water and Science Technology Board (WSTB) of the National Academy of Sciences/National Research Council focusing on the future of irrigation in the United States.

**FINDINGS:** Key results of the Collaborative Effort over the last year include (see 1993 and 1994 Annual Research Reports for previous findings)

- <u>Increasing the Amount of Collaborative Research Carried out by ARS and the Irrigation Industry</u>. Activities in this area have continued to focus on increasing the awareness of Irrigation Industry and ARS scientists and engineers about opportunities for collaborative research. For the fifth consecutive year, outreach efforts, including "how-to" information for entering into Cooperative Research and Development Agreements (CRADAs) with ARS, were extended through the Collaborative Effort exhibit at the 1995 IA Exposition, held in Phoenix. As in previous years, support for the exhibit was provided by IA and the ARS Offices of Technology Transfer, Interactive Cooperation, and Information. Staffing for the exhibit was provided by members of the U. S. Water Conservation Laboratory Irrigation and Water Quality Research Group in Phoenix and the Conservation and Production Research Laboratory, Bushland, Texas. Plans were initiated at the IA Exposition in Phoenix for an ARS exhibit at the Texas IA Exposition in 1996

  Through a Collaborative Effort initiative, the December 1995 issue of *Irrigation Business & Technology*, a bimonthly publication of the IA, included the first of what is to be a regular ARS feature on research and other irrigation and water quality information relevant to the irrigation industry. The articles will be coordinated by the office of the National Program Leader for Water Management and Water Quality. ARS irrigation and water quality locations will be contributors.
- <u>Proposing and Supporting the Water Science and Technology Board Irrigation Study</u>. A study, "The Future of Irrigation in the Face of Competing Demands," was proposed to the Water Science and Technology Board (WSTB)

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[1] Dedrick and Heermann (Water Management Research, Ft. Collins, Colorado) are co-chairs of the Collaborative Effort. Key input to the process has been provided by J. A. Chapman, Valmont Industries, Valley, Nebraska; L. E. Stetson, ARS, Lincoln, Nebraska; and S. A. Rish, ARS, Phoenix, Arizona, as Subgroup Co-Chairs; T. A. Howell, ARS, Bushland, Texas, for development of the "Yellow Pages"; and consultant D. B. Levine (Management/Team-Building Specialist) for overall facilitation of the Collaborative Effort.

of the National Academy of Sciences/National Research Council by the Collaborative Effort and initiated by the WSTB in 1993. Heermann served on the study committee, and Dedrick provided liaison between the Collaborative Effort Leadership Group and the study committee. Funding was provided by the Irrigation Association, USDA/ARS, USDI/Bureau of Reclamation, Ford Foundation, and Idaho Power Association. The study has been completed, and the report is scheduled for publication in the spring of 1996.

**INTERPRETATION:** The combined efforts of the irrigation industry and ARS have produced significant accomplishments, which can be expected to have continuing impact. Hundreds of industry representatives and other users have been reached through the annual IA Expo exhibits, the "yellow pages" directory of ARS Irrigation and Drainage researchers, and other materials. The new ARS article in *Irrigation Business & Technology* will reach a substantial number of users, one of the specific goals being to provide information on cooperative research opportunities. The forthcoming WSTB study report on the future of irrigation will be made available to the public and other interested parties. As with earlier WSTB studies, it can be expected to serve as an unbiased, in-depth, examination of the issues and, as such, to be used for policy and political decisions. Industry representatives to the Collaborative Effort continue to note how the process has provided a successful experience in building ongoing interaction, understanding, and trust between a client group, in this case the irrigation industry, and ARS. The approach used with the irrigation industry has potential as a model for building partnerships between ARS and other client groups, especially as ARS moves toward more client involvement in our research program development and assessment (i.e., ARS's response to the Government Performance and Results Act).

**FUTURE PLANS:** The Collaborative Effort Leadership Group, which last met formally in September 1993, has continued communication and interaction relative to ongoing activities, i.e., maintaining liaison with the WSTB study, meetings of the IA Research Committee, and outreach efforts. The next meeting is planned prior to publication of the WSTB study, with one of the goals to assess and recommend publicity strategies by the irrigation industry and others, including ARS. The other two Collaborative Effort thrusts, i.e., Identification of Priority Research Needs and Increasing the Amount of Collaborative Research Carried out by ARS and the Irrigation Industry, will be reviewed.

**COOPERATORS:** Representatives of the Irrigation Industry and ARS were shown in the 1993 Annual Research Report.

# HIGH-FREQUENCY, SMALL-VOLUME SURFACE IRRIGATION

D.J. Hunsaker, Agricultural Engineer; A.J. Clemmens, Supervisory Research Hydraulic Engineer; and W.L. Alexander, Agronomist

**PROBLEM:** The ability to apply light, frequent deliveries of water to crops with microirrigation is well recognized. However, very few attempts have been made to develop high-frequency, small volume irrigation management strategies for surface irrigation systems. This is because 1) most traditional surface irrigation methods are not capable of delivering small uniform quantities of water to the field, 2) changing surface irrigation system designs to accommodate smaller applications may require a large capital investment, 3) increasing irrigation frequencies will likely increase operating expenses, and 4) more frequent irrigation scheduling will require a higher degree of management.

However, cumulative research suggests that increased irrigation frequency has an effect on crop yields that could be economically significant. A number of recent research studies conducted in the Desert Southwest have demonstrated higher yields for surface-irrigated cotton when irrigation occurred more frequently. One investigation reported 25% higher yields with irrigations applied once every five days during the cotton's boll development period, rather than once every 10-14 days. In addition to potentially higher crop yields, surface irrigation systems that can apply small application amounts uniformly could reduce irrigation water use and decrease deep percolation and fertilizer losses.

In recent years, advances in irrigation technology have brought about a new brand of high-performance surface irrigation systems that have been implemented successfully. For example, precision land-leveling has made possible the development and use of level basin irrigation systems, which, when properly designed and managed, allow more uniform water distribution over the field and smaller water applications.

Partially prompted by the research mentioned above, we conducted investigations in 1993 and 1994 on high-frequency, small-volume level basin irrigation for cotton. The objectives were to determine the effects of small, frequent water applications on the hydraulic characteristics and irrigation performance of the level basin system and on the water use, growth, and yield of cotton; and to develop and evaluate the economic feasibility of a high-frequency level basin design for cotton production in the southwestern United States.

In 1995, we began an investigation on high-frequency irrigation for sweet corn in Coachella Valley, California, in cooperation with the Coachella Valley Resource Conservation District. The objective of that study was to evaluate corn yield response to high-frequency irrigation under a sloped furrow irrigation system.

**APPROACH:** Details on the procedures for the level basin cotton irrigation studies conducted at The University of Arizona, Maricopa Agricultural Center, were previously presented in the 1993 and 1994 USWCL ARRs. Briefly, the studies were conducted in farm-scale level basins (14 by 250 m), as well as small basins (10 by 10 m). Two irrigation managements were included in the studies: 1) low-frequency, large volume irrigation (LF), and 2) high-frequency, small volume irrigation (HF). The period in which frequent, small volume irrigation was applied to the HF treatment was generally confined to a four-to-five week period coinciding with the boll development stage of the cotton (≈during July). Furrows within the HF treatment were smoothed and compacted three times early in the season using a weighted device shaped like a torpedo. The total seasonal water application was approximately the same for the LF and HF treatments. Data obtained during the field studies were used to analyze the effects of the treatments on infiltration, soil roughness, distribution uniformity, evapotranspiration, cotton growth, and final lint yield.

Two level basin irrigation system designs were developed for a hypothetical cotton field (300 by 800 m) in central Arizona. One system was to be operated at low-frequency irrigation cycles, the other at high-frequency irrigation cycles beginning at boll development. Systematic, repeated application of the irrigation simulation model, SRFR, was used to arrive at the design length and furrow inflow for each system based on the criteria that the low-quarter distribution uniformity be greater than 85%. Parameter values for infiltration, soil roughness, and furrow geometry derived from the field studies for the LF and HF treatments were used in the simulations. The economics of the two systems were evaluated and compared by considering the costs for system installation (including land-leveling, canals, and turnouts); production, water, overhead, and land ownership costs; and the expected gross income from the cotton produced in the system. Cotton water use and lint yield used in the economic evaluation were described by the results obtained in the field studies for the LF and HF systems.

Sweet corn grown under high-frequency furrow irrigation was studied in the Coachella Valley in 1995 on a local grower's field. The corn was planted in mid-January and harvested in early May 1995. The field length was 385 m, and the gradient was 0.20%. The end of the field was blocked to eliminate surface runoff during irrigation.

Several irrigations were applied to the corn during February and March. In early April, two sections of the field, each consisting of 13 rows of corn, were identified as treatments for our study. Between April 6 through April 27 (silking and yield formation), one section (high-frequency) was irrigated twice every three days, while the other section (low-frequency) was irrigated once every three days. During that period, water application depths for the high-frequency section were on the order of 12 mm, while they were about 18 mm for the low-frequency section. Field measurements made during irrigations included furrow inflow and duration, furrow advance time, and surface water elevation. Measurements made before and after irrigation included infiltration and soil water content. In each section, the entire length of one central row of corn was hand-harvested on May 3.

FINDINGS: Some of the findings from the level basin field studies were presented in the 1993 and 1994 USWCL ARRs. Table 1 summarizes several of the key findings from the studies.

Figure 1 shows the high- and low-frequency level basin system designs that were implemented on the hypothetical field in central Arizona, respectively. Figure 2 shows a comparison of the annual costs of the two systems that were associated with system installation, water, cotton production, overhead, and land ownership for the two systems. The price for irrigation water was assumed to be $0.42 per mm-ha ($52 per ac ft). Figure 3 shows the total annual costs and the expected gross incomes for the two systems. The cotton price was assumed to be $1.61 per kg lint ($0.73 per lb).

All of the results from the 1995 sweet corn study have not been analyzed. However, preliminary results indicate that the corn yield was 14% higher under the high-frequency than low-frequency schedule.

INTERPRETATION: Devices to smooth and compact furrows, such as the torpedo device used in this study, can significantly decrease soil roughness and increase water advance across furrows during early season irrigations. Applying frequent irrigations during rapid boll development significantly decreased infiltration. However, the low-quarter distribution uniformities were generally lower than those for the low-frequency treatment when the smaller applications were given during boll development. Although applying high-frequency irrigation during boll development produced an average lint yield 10% higher than the low-frequency, the increase was somewhat lower than that found by other investigators.

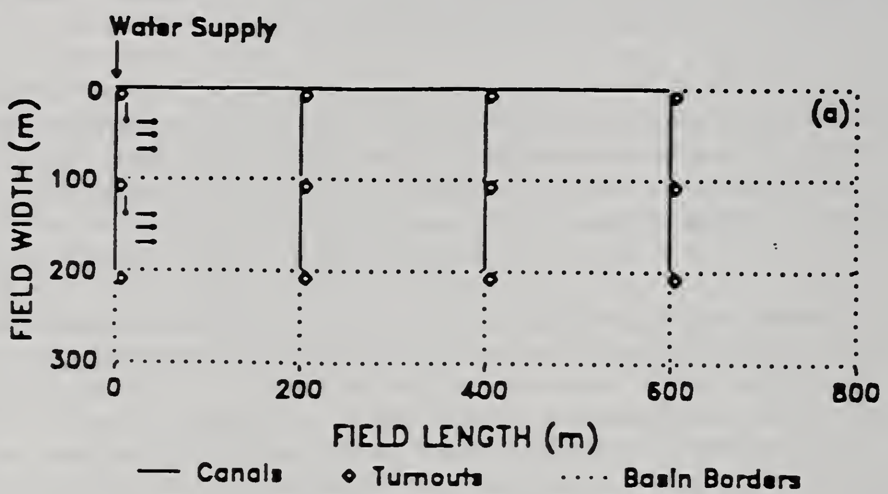
The advantage for the low-frequency over the high-frequency system was that a longer field length could be used in applying uniform water applications. Although this reduced canal costs compared to the high-frequency design, that cost benefit was offset by higher land leveling costs. Consequently, the installation cost for the two systems was nearly the same. Although the total cost required to install and produce cotton with the low-frequency system was slightly lower than the high-frequency system, the economic analysis suggested that the high-frequency system was more profitable. The most prominent economic benefit from high-frequency level basin management is potentially higher yields. Based on yields obtained in the field studies, the 10% higher yield for the high-frequency treatment represented a gross income $230 per ha above that for the low-frequency. A difference in gross income of that magnitude could make high-frequency design and management appealing to growers operating under a small profit margin.

FUTURE PLANS: Further studies of high-frequency irrigation management are needed to establish specific practices that optimize yields under surface irrigation. Development of high-frequency, small volume level basin irrigation will continue in 1996. Future work includes plans to evaluate the effect of continuing high-frequency irrigation beyond the boll development period. Additional studies will be continued with corn and other surface-irrigated vegetable crops.

COOPERATORS: D.D. Fangmeier, Department of Agricultural and Biosystems Engineering, The University of Arizona; and Don Ackley, Coachella Valley Resource Conservation District, Indio, CA.

Table 1. Summary of key findings from the 1993 and 1994 level basin studies.

| Parameter | Finding |
|---|---|
| Soil Roughness | The Manning roughness coefficient was reduced during early season irrigations by about 50% in furrows that were torpedoed. |
| Infiltration | Infiltration was reduced by 25% in the high-frequency treatment during the boll development period. |
| Distribution Uniformity | The low-quarter distribution uniformities were 4 to 10% lower in the high-frequency treatment during boll development. |
| Evapotranspiration | There was an average increase in evapotranspiration of 6% in the high-frequency treatment. |
| Final Yield | Lint yields averaged 10% higher in the high-frequency treatment. |



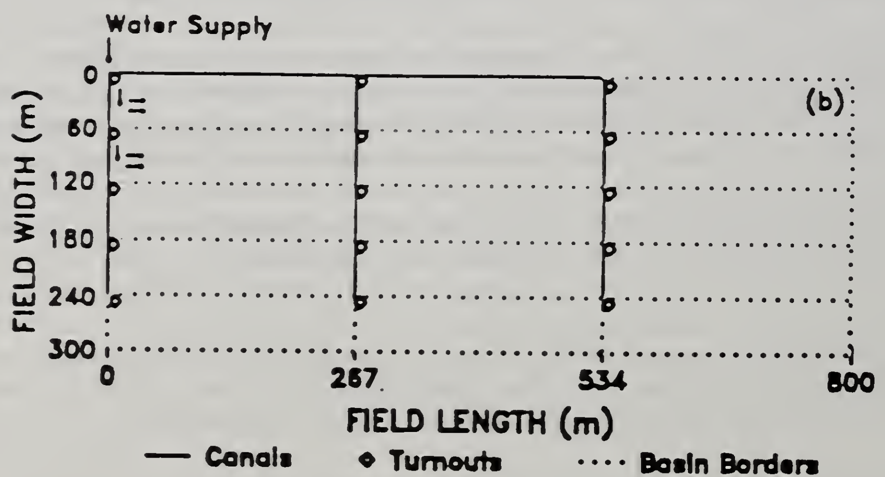




Figure 1. Field configuration for high-frequency (a) and low-frequency (b) designs.

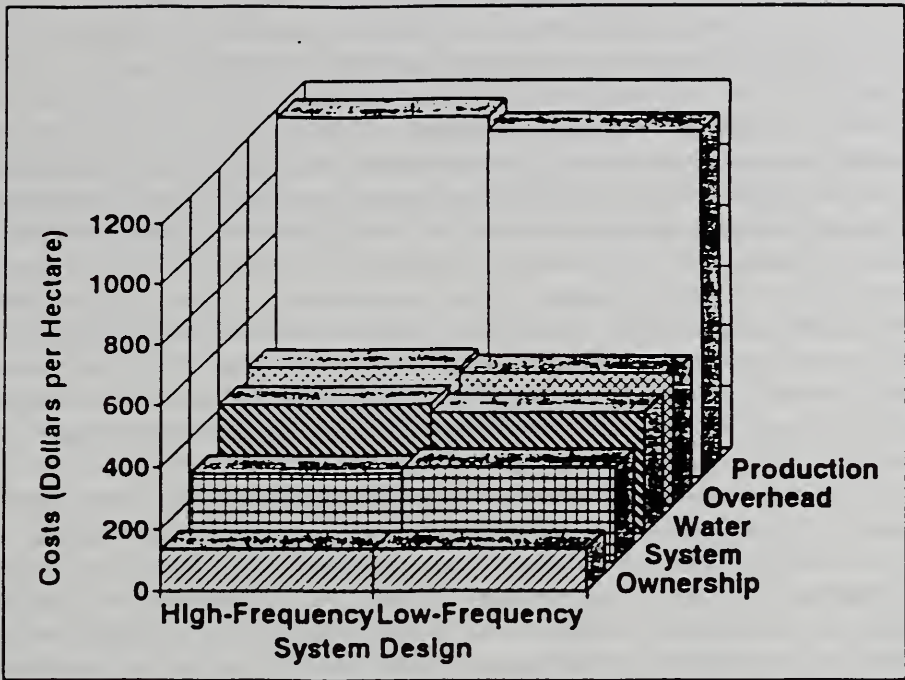



Figure 2. Itemized annual costs of cotton production for high-frequency and low-frequency irrigation system designs.

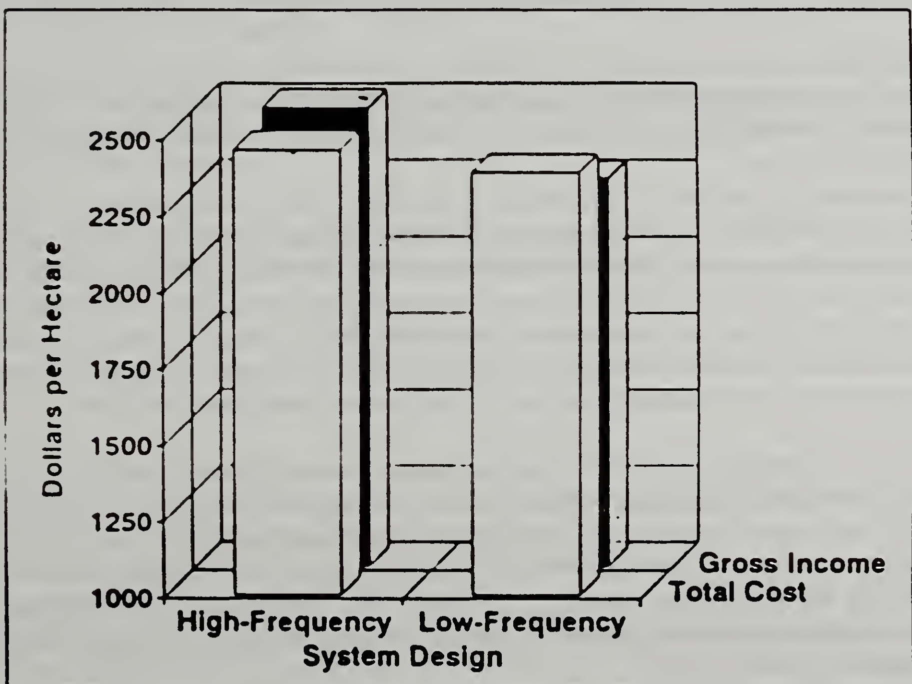



Figure 3. Total annual costs and expected gross incomes for the high-frequency and low-frequency irrigation system designs.

## SURFACE IRRIGATION MODELING

T.S. Strelkoff, Research Hydraulic Engineer;
and A.J. Clemmens, Supervisory Research Hydraulic Engineer

**PROBLEM:** Throughout the irrigated world, water is applied to fields unevenly and locally in excessive amounts, leading to wastage and to pollution of surface and groundwaters receiving the excess. The interaction of the many variables significantly influencing the movement of irrigation streams down fields, and, ultimately, the distribution of infiltrated water and the amount of runoff from the irrigation, is too complicated for simple calculation. A mathematical model–a numerical computer solution of the pertinent governing equations–supplied with the conditions of the irrigation can, on the other hand, allow rapid determination of the consequences of a given physical layout and proposed management procedure. Systematic, repeated simulation allows determination of design parameters to yield optimum uniformity of infiltrated water and minimum runoff from the end of the field. This, in turn, can reduce the degradation of groundwater supplies by excess irrigation water, contaminated by fertilizers and pesticides, percolating below the root zone of the crop. Similarly, reduction and re-use of field runoff protects surface-water supplies downstream from irrigated fields.

Current models of surface irrigation require further development to extend the range of conditions they are designed to simulate and to increase the reliability of their mathematical procedures. New irrigation techniques generally precede attempts at simulation, so models must be revised to allow theoretical study of the innovations. Furthermore, present models do not always complete a simulation. A variety of physical conditions that can derail a simulation include streams that shrink in length following, say, cutback; very low flows in furrows or borders that exhibit variations in properties with distance; and following surges overtaking earlier releases. The current ARS surface irrigation model, furthermore, requires data entry more complicated than many potential users are willing to negotiate.

Most current models, furthermore, are limited to one-dimensional flows, for example, single furrows, or border-strips with zero cross slope and a uniformly distributed inflow at the upstream end. Large basins are currently being irrigated from a single corner inlet, or from one placed in the middle of a side. The flow spreads out from the inlet in all possible directions, and any one-dimensional simulation of the distribution of infiltrated water must be viewed as a very coarse approximation. Furthermore, actual departures in the basin surface from a theoretical horizontal plane influence the flow of water thereon, with the irrigation stream concentrated in the lower-lying areas; this has significant potential for affecting infiltration uniformity. Only a two-dimensional model can simulate these factors with any accuracy.

**APPROACH:** For one-dimensional simulation, user-friendly, menu-driven data input and output, the latter as graphs and text, are linked to a reliable simulation engine based on the universal laws of hydraulics. Constants in commonly accepted empirical equations for infiltration and roughness are entered as input. Program development involves extensive coding in both FORTRAN and C++.

Two-dimensional simulation is also based on hydraulic principles. Under the assumption of flow velocities small enough to allow neglect of accelerations (well established in the surface-irrigation context), force components in each of two mutually perpendicular directions on the field are in equilibrium. The resulting parabolic partial differential equations in the two directions and time yield a wave-like solution encompassing both wet and dry areas of the field. Calculated depths of flow in the nominally dry areas are many orders of magnitude smaller than those calculated within the irrigation stream, making demarcation of a nominal advancing wetting front easy. Infiltration is assumed to begin only after this wetting front arrives, and to stop after the calculated depth drops below a specified small value.

**FINDINGS:** Release of a user-friendly, menu-driven one-dimensional surface-irrigation model, SRFR, version 3.0, has been delayed, but is approaching completion and distribution to cooperating researchers. The combination of a graphical user interface for input and output (consisting of ZINC menus programmed in WATCOM C++ code) linked to a simulation engine (written and compiled in WATCOM FORTRAN) has proved reasonably reliable (certain run-time errors, however, lead to a keyboard freeze requiring a re-boot). The result is a single 1.6MB executable file. On contemporary PCs possessing extended memory beyond the 640K DOS range, execution is enabled through the DOS4GW memory manager distributed by WATCOM.

A pilot version of a two-dimensional model allowing specification of variable bottom elevations has been constructed on the basis of a nonlinear, implicit numerical scheme with the resulting simultaneous equations solved for a series of one-dimensional formulations in alternating directions at each time step (Tamimi, 1995). With isotropic roughness, the drag

force at any location in the field is oriented collinear with and opposite in direction to the vector velocity of flow; the hydraulic conveyance in this case is a scalar. For anisotropic roughness, e.g., as the result of some tillage practices which leave small corrugations parallel to one side, the drag and velocity vector are not collinear; i.e., the gradient of water-surface elevation lies at some angle to the resultant flow velocity. In this case, the conveyance is a tensor quantity.

The model was subjected to some preliminary testing in both one-dimensional and two-dimensional contexts. Results from a one-dimensional subset of the model were compared with the results of SRFR, which limits computations to the wetted portion of a border-strip or basin, expanding and contracting the region of computation with the advance and recession of the irrigation stream. Figure 1 compares the two calculations of advance, recession, and the distribution of infiltrated water for a basin exhibiting 10 *mm* standard deviation in bottom elevations. The agreement suggests that the two quite different numerical techniques both really do solve the one-dimensional partial differential equations of surface irrigation hydraulics.

Two-dimensional testing utilized field data gathered in a 3 ha essentially rectangular basin on the Gila River Farms, an agricultural enterprise within the Gila River Indian Community. The flow to the inlet to the basin, in the middle of a long side, was monitored, as were flow depths at some 28 points in the field; before and after the irrigation, the field was surveyed for elevation differences. Figure 2 shows the simulated advance contours–successive positions of the wetting front at 15-minute intervals, while figure 3 is a comparison of measured and simulated advance, in terms of fraction of total area wetted as a function of time. Figure 4 shows a similar comparison of measured and simulated recession.

**INTERPRETATION:** To make a significant impact on surface-irrigation design and practice, computer models of the process must be of broad scope, fast, and reliable, yielding simulations for every reasonable combination of circumstances, and with convenient, user-friendly data input and graphical display of the results of any given set of design and management parameters. This is the aim of current development in both the one-dimensional and two-dimensional contexts. A simulation model capable of providing quick results for various test combinations of design and management parameters would allow these to be optimized.

**FUTURE PLANS:** Current deficiencies in one-dimensional-model behavior as outlined above will be addressed, exploiting the ZINC-WATCOM development-software combination. The pilot two-dimensional model will be extended to non-rectangular field configurations, and numerical solution parameters will be adjusted automatically in response to solution behavior; a general review of these parameters will be undertaken with the aim of speedy, robust performance. Additional field verification will be sought.

**COOPERATORS:** D.D. Fangmeier, University of Arizona; Dr. Behzad Izadi, University of Idaho; Keith Admire, Natural Resources Conservation Service (formerly, SCS), Dexter, MO; Marshall English, Oregon State University, Gila River Farms, Pinal County, Arizona.

**REFERENCES:** Tamimi, Akrum H. 1995. *Two-Dimensional Transient Flow in Non-Level Irrigation Basins.* Dissertation submitted in partial fulfillment of the requirements for the Ph.D. degree, University of Arizona. 160 pp.

# SOFTWARE FOR THE DESIGN AND MANAGEMENT OF SURFACE IRRIGATION SYSTEMS

T.S. Strelkoff, Research Hydraulic Engineer;
and A.J. Clemmens, Supervisory Research Hydraulic Engineer

**PROBLEM:** Surface irrigation, in general, is perceived as an inexpensive low-efficiency method of irrigating crops, bound by inherent characteristics and traditional practices to wasting much if not most of the water applied. Furthermore, irrigation water that passes through a farm and exits either as runoff into surface drainage or as deep percolation heading to an aquifer is often chemically changed through contact with soil salts, fertilizers, and pesticides. More efficient irrigation would reduce return flows from irrigation to a minimum and so reduce the potential for contamination of surface and groundwater supplies.

Suggested alternatives include conversion to sophisticated high-tech equipment for point application—microirrigation—or simply retiring agricultural land out of production. While limitations on application efficiency *do* exist, depending upon specific field conditions, current procedures for designing field dimensions and operational parameters are simply inadequate. The complexity of surface-irrigation hydraulics has led to design and management that are largely empirical and often greatly dependent on individual judgment and experience; formal design procedures like those of the NRCS are based in part on broad assumptions of uncertain applicability.

In recent years, the hydraulic complexity of surface irrigation has been largely overcome through the development of simulation software based on the universal laws of hydraulics and capable of predicting the performance of an irrigation, given extant field conditions, physical layout, and operational parameters. Each simulation, however, taking anywhere from a fraction of a minute to several minutes to perform on contemporary PCs, yields the results for just one set of conditions. Before such results can be used in design, some procedure is needed to lead the user from a trial set of design parameters to a better one, in the search for an optimum. Further, a program for design should indicate what the best possible performance can be, as limited by extant field conditions, as well as how to achieve it. And it should indicate how management should respond to changes in field parameters over the course of a season.

Recently, sophisticated design and management criteria, based on a database of previously calculated simulations, have been applied to laser-levelled surface-irrigated basins. As a result, efficiency of water application on such basins can be achieved at a level approaching that of microirrigation, at far less expense. For sloping fields with tailwater runoff, on the other hand, efficiencies of water use lag that in level basins by 20% or more. Yet such fields represent the predominant layout in many areas, in the U.S. and abroad. Conversion to level basins is not always technically feasible, as when field slope is great and agricultural soils shallow. Furthermore, the cost of conversion to level basins or capital-intensive systems like LEPA (low-energy precision applications) or microirrigation can be substantial. With irrigated farming in many parts of the world under severe economic pressure, attainment of conservation goals without expensive conversions is especially attractive.

**APPROACH:** Any indicator of performance $P_i$ of an irrigation depends on field characteristics (infiltration, slope, and roughness), target depth of infiltration, $d_{req}$, border-strip or basin dimensions (length $L$ and width $W$), and inflow rate $Q_{in}$ and application time $t_{co}$. In other words, $P_i = f(k, a, S_0, n, d_{req}, L, W, Q_{in}, t_{co})$. It is assumed that the dependence of cumulative infiltration $d$ on opportunity time $\tau$ can be estimated by the empirical Kostiakov formula, $d = k\tau^a$, bottom slope is uniform and given by $S_0$, and roughness can be characterized by the Manning $n$. The first four arguments are given field characteristics, and the remainder are design and management parameters. The purpose of the software is to provide the function $f$ for a series of pertinent performance indicators $P_i$.

To provide this capability, a large number of simulations is performed, once and for all, to form a database for a design program. Interpolation amongst the tabulated values in the data base allows solution within a continuous spectrum of independent variables. Indeed, in earlier studies, thousands of dimensionless simulations were performed. Nondimensional representation was employed to allow coverage, with only this number of simulations, of a very broad spectrum of irrigations in level basins and in sloping borders with tailwater runoff. In the simpler case of level basins, coordinate transformations coupled to successions of simulations led to a store of dimensionless data on uniformity, advance time, etc., as functions of unit inflow rate and basin length. From these data, all pertinent performance parameters can be derived for any real basin.

In the sloping border case, dimensionless simulations were performed in hypothetical border strips of such great length that the stream never reaches field end. The dependent variables stored from each run were the length and shape of the

distribution profile of infiltrated water; any infiltration calculated beyond actual border-strip length constitutes the runoff for that border strip. It proved possible to fit the distributions of infiltrated water for the various simulations by a two-parameter function. Given a real or hypothetical design border, all the conditions governing the irrigation are known, and it could be simulated. But in the design approach, the commensurate dimensionless input variables can now be determined for entry into the stored data, and any performance indicator of interest (distribution uniformity, runoff, application efficiency, etc.) can be derived from the resultant shape parameters far more quickly. The capability of determining the results of any simulation within a second or two suggests presenting a whole screenfull of information on the variation of chosen performance parameters with design input parameters varying over a wide range. Such curves could show the performance *possibilities* for the given field conditions as well as the necessary values of design parameters to achieve a given level of performance.

In both level basins and sloping border strips, dimensionless advance *vs.* time curves were also stored to allow either cutoff time $t_{co}$ or advance distance at cutoff $R$ to represent the duration of the application. Design based on $R$ is potentially a significant improvement, since that is often how such systems are actually operated.

FINDINGS: Software for designing level basins is now in its second release (version 2.0). The principle performance indicator is distribution uniformity, $DU$. After specifying the field conditions ( with $S_0=0$) and target depth, the user, in design mode, can specify three variables out of the four–$L$, $W$, $Q_{in}$, $DU$, and the program supplies the remaining one, as well as $t_{co}$ (or $R$). In evaluation mode, in essence an essentially instantaneous simulation, the user specifies the field parameters, dimensions, inflow and cutoff time (or $R$), and the program yields $DU$ and the minimum or low-quarter depth in the infiltration distribution.

Software for sloping border strips, initiated under contract with the Arizona Department of Water Resources (ADWR), is nearly complete. A surface-irrigation software user and advisory group, established to review this work, has had the opportunity to view the capabilities of the program. For example, figure 1 shows the graphical output of the evaluation mode. The distribution of infiltrated depths and the values of a series of performance indicators for a particular set of field conditions and design and operational parameters are shown. Figure 2 displays contours of a particular performance indicator, potential application efficiency, for given field conditions, an available maximum stream size, and a given target depth of infiltration. The design variables here are the border-strip length and width. The contours show what efficiency is *possible* for the given field conditions, as well as what combinations of length and width will achieve it. Since it takes only a few seconds to generate the contour map, a series of such graphs for different target depths, or for changes in, say, infiltration characteristics over a season, can be printed out in hard copy, or tiled on the screen, for comparisons.

Faced with an established physical design ($L$, $W$) in a given field, variation in the management parameters $Q_{in}$ and $t_{co}$ (or $R$) determine performance. Figures 3 and 4 exemplify results of the management mode in the software. Figure 3 shows the low quarter depth of infiltration for various combinations of inflow and application time, while figure 4 shows the corresponding potential application efficiency.

INTERPRETATION: There is potential for water conservation and reduction of influx of agricultural chemicals into the environment by improved design and management of surface-irrigation systems. Efficiencies can be limited by field conditions, but significant improvement over common current values is feasible. Software based on mathematical simulations of irrigations can assist greatly in optimizing water use. A fast, reliable, user-friendly computer program showing the response of the irrigation system to variations in trial design conditions should be attractive to potential users. These users would most likely be those persons advising growers–mobile evaluation laboratory personnel, NRCS field personnel, extension personnel, consultants, and irrigation district personnel.

FUTURE PLANS: The BASIN program will be provided with a component accounting for the influence of imperfect levelling. The BORDER design program will be completed for release. On-line and hard-copy documentation will be prepared. A proposal for extension of the sloping-field design program to furrows, the predominant method of surface irrigation, is under review by the ADWR.

**COOPERATORS: Alan Fehrman, ADWR, Phoenix; Harold Blume, Natural Resources Conservation Service (formerly, SCS), Phoenix; Kris Johnson, Buckeye-Roosevelt Natural Resources Conservation District; D.D. Fangmeier, University of Arizona; Ed Martin, University of Arizona Cooperative Extension.**

# MODELING THE INFLUENCE OF LAND LEVELING PRECISION ON SURFACE IRRIGATION PERFORMANCE

A.J. Clemmens, Supervisory Research Hydraulic Engineer; and
T.S. Strelkoff, Research Hydraulic Engineer

**PROBLEM:** Surface irrigation systems inherently distribute water nonuniformly over the land area to be irrigated. This nonuniform distribution of water can cause a number of problems. First, areas receiving too little water can experience crop stress, yield reductions, and, from insufficient downward movement of water, salinization. Those areas receiving too much water can leach fertilizers and contribute to rising water tables, again leading to salinization. Farmers tend to over-irrigate so that their crops will not be stressed from underirrigation. However, this leads to excess deep percolation and rising water tables on adjacent lands. These problems are much more acute on reclaimed lands. Poor irrigation uniformities increase the amount of time needed to bring reclaimed land into full production.

One of the main contributors to surface irrigation uniformity is the precision of land leveling. Greater precision is needed as land slopes get flatter, with level basins requiring a high degree of land leveling precision in order to obtain reasonable uniformities. Experiences in the U.S. indicate significant improvements in irrigation uniformity and efficiency with improvements in leveling precision on level basins. While some information on leveling precision and its influence on production is available, the degree to which leveling precision in Egypt and elsewhere affects crop production and water management is not fully known.

Mathematical models of the advance and recession of water over a surface irrigated field are useful tools for predicting irrigation uniformity and efficiency. However, currently available models can handle only major undulations in the field surface, and only in one dimension. They can fully model neither the two-dimensional nature of water flow in basins nor multiple furrows.

**APPROACH:** NARP, through OICD, has funded a cooperative project with the above title between this research unit and Moshtohor University in Egypt. Existing surface irrigation models are used in this study to take a first look at the effects of surface irregularities on uniformity. Part of this project is to extend the existing irrigation models to multiple furrows and/or two dimensions so that they can more adequately handle real field conditions. Field data were collected to determine existing conditions in Egypt and for verifying the models developed. Existing land leveling and tillage practices are being evaluated to determine their influence on leveling nonuniformity. Finally, assessments will be made regarding the magnitude of the impact of poor land leveling in Egypt, and design and management guidelines will be developed to aid in making decisions for improvement in surface irrigation practices, including recommendations on leveling and tillage practices. This is expected ultimately to improve the effectiveness of water use in irrigated agriculture, both in Egypt and the U.S.

**FINDINGS:**

Egyptian field conditions defined: Nile cracking clay soils behave somewhat differently from typical cracking clay soil in the U.S. in terms of infiltration properties. These soils exhibit a high final infiltration rate relative to typical U.S. clay soils (cracking and noncracking). This significantly affects the field designs (inflow rates, lengths, etc.). Soil resistance to flow also proved to be much higher on Egyptian soils, partially due to the large clod sizes under current tillage practices. Crop resistance to flow also appears to be much higher, likely due to higher planting densities. The effect of higher flow resistance is to require larger inflow rates and shorter basin lengths to achieve good uniformity.

Irrigation simulation models verified: One aim of the field experiments was to provide independent verification of the SRFR simulation model for borders, basins, and furrows. These studies showed that the advance of the irrigation stream could be predicted accurately if accurate estimates of infiltration and roughness parameters were provided. Further improvements were made in the simulation model's ability to handle highly undulating field surfaces; i. e., those typical of Egyptian traditional leveling practices.

Furrow spacing: Preliminary studies indicate that for modern long-furrow irrigation, furrows spaced at 75 cm performed better than furrows spaced at 60 cm. This resulted from a larger furrow cross section and, consequently, the larger flow rates that could be applied. Increasing the spacing to 1 m did not significantly improve performance.

Basin inflow rate: Preliminary studies indicate that inflow rates to long wheat strips need to be above 2 LPs/m (e.g., 3 to 4 LPs/m) to overcome small-scale roughness effects that cause slow advance and poor efficiency. This is shown by the values of Manning n and depth infiltrated at one hour given in Figures 1 and 2. Manning n values drop sharply above

2 LPs/m and after the first irrigation on wheat. Irrigation uniformity was also improved when furrow flow rates on cotton were above 2 LPs per furrow.

Analysis of uniformity effects: Simulation studies indicate that statistical procedures can be used to evaluate the influence of a nonlevel field surface on irrigation uniformity. Figure 3 shows a comparison between the proposed statistical equation for low quarter distribution uniformity ($SDU_{lq}$) and the results from Monte Carlo simulation when the effects of land leveling precision were included. Here agreement is very good. However, the effects of field nonlevelness on advance was greater than anticipated. Figure 4 shows a comparison between $SDU_{lq}$ and the $DU_{lq}$ from simulation with SRFR when a nonlevel field surface was used as input. The difference between Figures 3 and 4 results from a slowing of advance due to the non-level surface. (This is only one of several comparisons; others are worse). SRFR, however, overestimates the influence of field nonlevelness since it simulates a representative unit width of field (i.e., the same elevation across the width). Variations in elevation across the width would reduce the differences suggested by Figure 4. Further study with a two-dimensional model is needed to evaluate properly this effect and its implication on long-basin/furrow design.

Laser land leveling: Field studies on wheat showed that laser land leveling with mechanized planting provides significant improvement in germination, crop stand, harvest time, and profit. For example, grain yields were increased from 1.5 ton/fed to 2.5 ton/fed; combine-harvesting time was reduced by 36%, and profit increased from LE 232/fed to LE 1299/fed.

Seedbed preparation: Use of a rototiller following chisel plowing for seedbed preparation resulted in a potentially significant reduction in tillage cost. Chisel plowing alone required five passes to provide the proper seedbed, while the rototiller-chisel plow combination required two passes, one with each implement. Fuel cost was reduced by more than 70% from 25 to 6 liters of fuel per feddan.

**INTERPRETATION:** Improvements in tillage/irrigation methods have the potential for making significant improvements in productivity and water management on the surface-irrigated land within Egypt. It has been found that tillage and irrigation practices must be improved in combination to obtain the positive results from each and from other agricultural inputs. Achievement of this goal will require significant extension effort—hand-in-hand with additional applied research—to assure that these methods are properly applied.

The application of mathematical models to problems in Egyptian irrigation have provided U.S. irrigation experts with additional tools to analyze surface-irrigation efficiency and uniformity, which can be used to provide appropriate recommendations for design and management of surface irrigation systems.

**FUTURE PLANS:** This project has been officially terminated. Some cooperation is expected to continue in finalizing manuscripts for publication based on the cooperative research. Further, more analysis needs to be performed with the 2-D model to determine the true impact of basin nonlevelness on 2-D basins. Better guidelines and analysis of uniformity can then be implemented within the BASIN program.

**COOPERATORS:** Z. El-Haddad, M. El-Ansary, and H. Osman, Department of Crops and Agricultural Engineering, College of Agriculture, Moshtohor Zagazig University, Egypt; and D. Fangmeier and A. Tamimi, U. of Arizona.

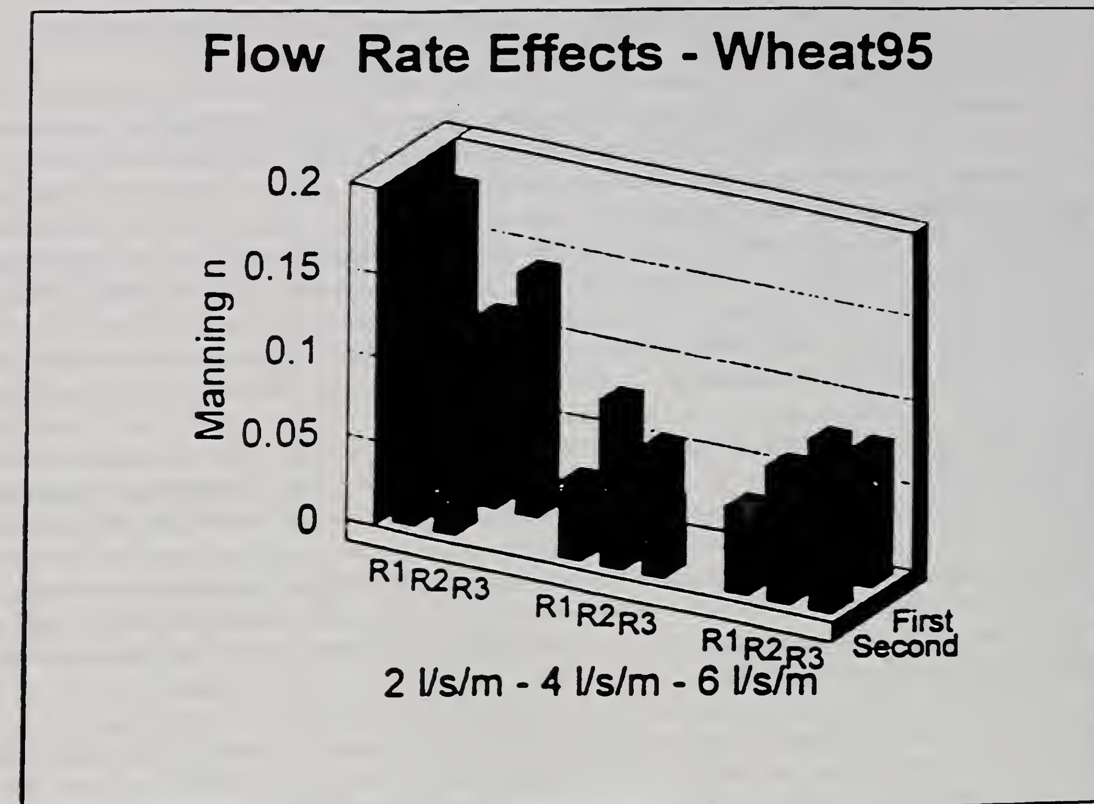



Figure 1. Effects of flow rate on Manning n – Wheat '95.

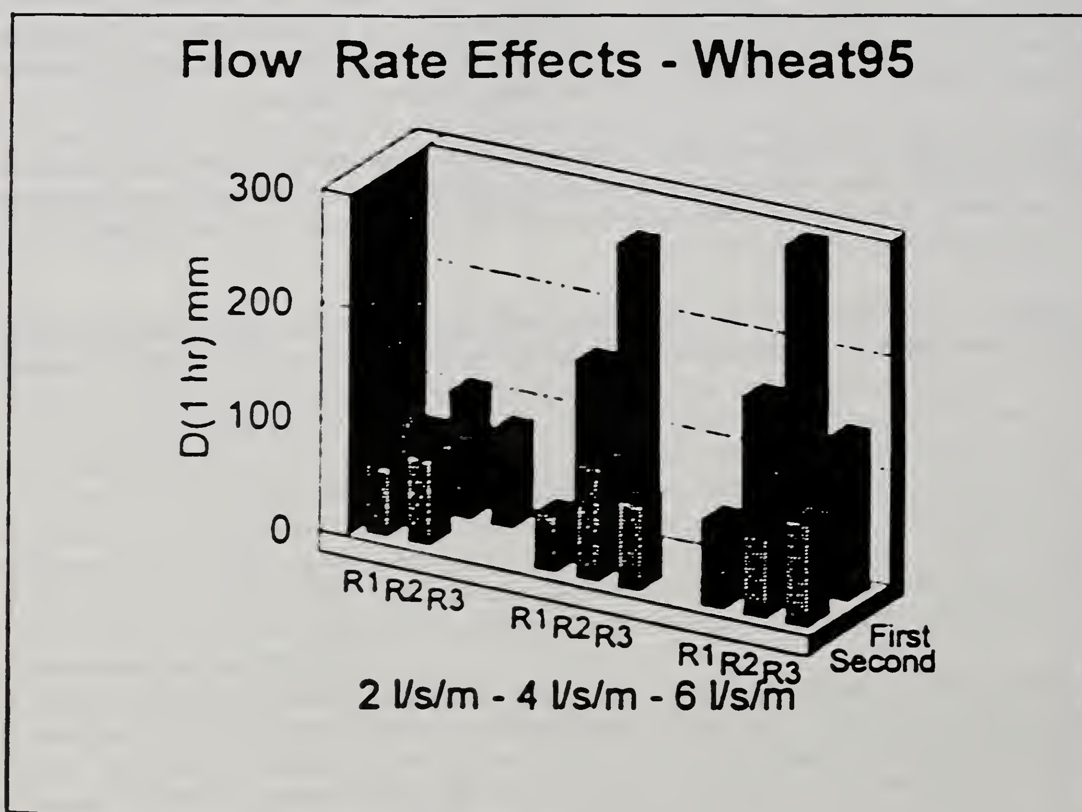



Figure 2. Effect of flow rate on depth infiltrated in one hour – Wheat '95.

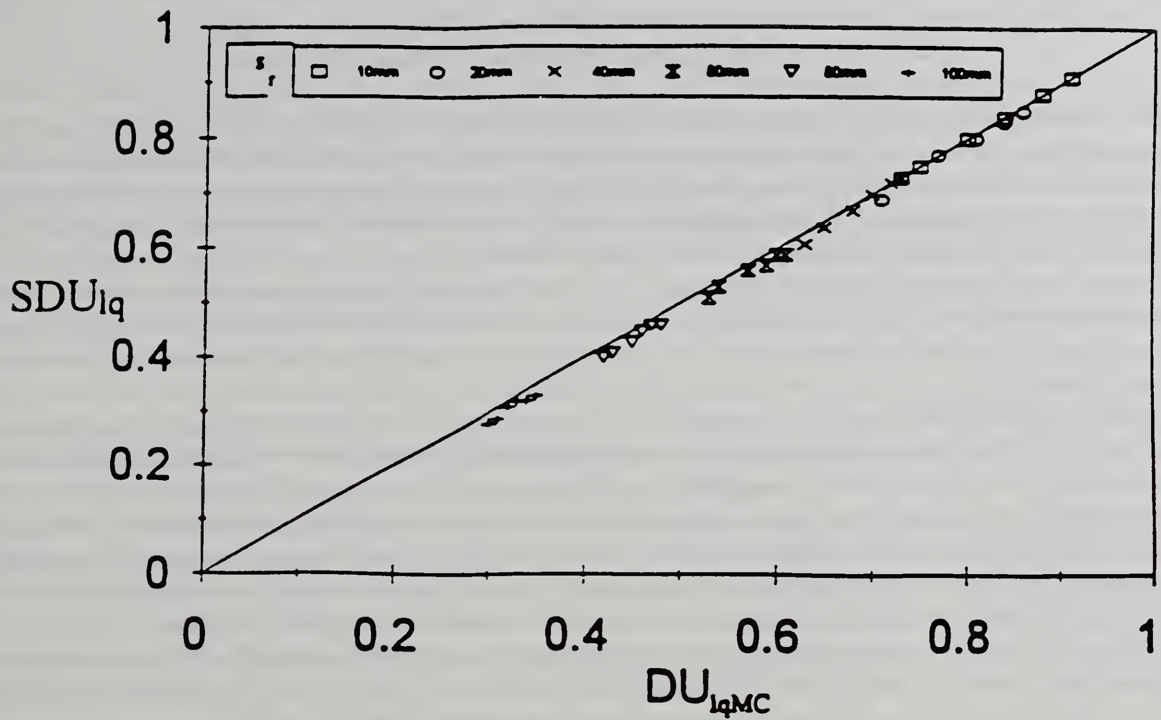



Figure 3. Compairson between statistical low-quarter distribution uniformity, $SDU_{11}$, (expected value) and the average low-quarter distribution uniformity from Monte-Carlo simulation, $Du_{lq\text{-}MC}$.

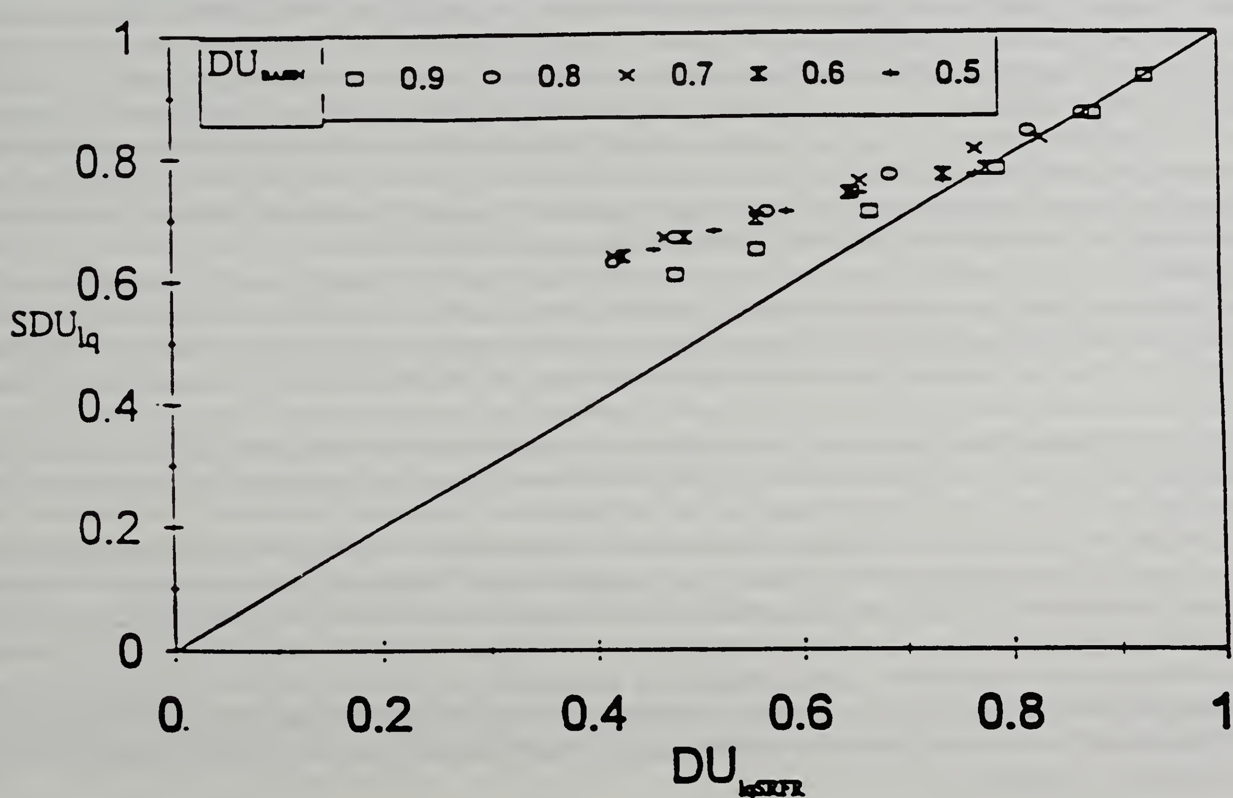



Figure 4. Comparison of low-quarter distribution uniformities $SDU_{lq}$ and $DU_{lqSRFR}$ with cutoff based on distrance for R = 0.85.

# CANAL BEHAVIOR AND RESPONSE TO TRANSIENTS

T.S. Strelkoff, Research Hydraulic Engineer;
and A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Efficient use of irrigation water often depends on the timely availability of the required flow rates for the required period of time. But even if the supply system consists of expensive pipelines, there is no guarantee that with a large number of users on a line, the pressure required to deliver a required rate at a distal point would be available. In the case of the far more economical and prevalent *canal* supply systems, delivery upon demand is considerably more problematic. In a closed conduit, even though pressure drops can limit the outflow at any offtake, any changes in flow anywhere are immediately reflected throughout the system. In an open channel, with the water surface free to rise or fall, changes in discharge propagate as large-scale gravity waves, moving not much faster than the water velocities themselves. It could be hours before a demand initiated at a downstream point can be satisfied by increases in discharge at the upstream end, if at all.

These circumstances have led, on the one extreme, to the common practice of prior scheduling of user demands for canal operations, i.e., making the appropriate pump and control-gate settings in advance. At the other extreme, a variety of supervisory or feed-back control schemes have been proposed to respond to demands initiated at will by a user. Even with advance scheduling, the setting of the gates is often based on the subjective judgment and intuition of personnel with varying degrees of experience; it is often inordinately time-consuming and inaccurate. Measures appropriate to anticipated demands are being studied with inverse schemes of solving the governing flow equations. Strategies for control based on measured canal responses to varying demands, in a feedback loop, are also being considered.

Experience shows, however, that in any case, given control measures have different degrees of success in different canals, depending upon slope, discharge, and other canal-flow parameters, so far in an unpredictable way. This report deals with quantifying the influence of flow properties on canal response to control measures.

APPROACH: A change in flow rate in a canal is generally accompanied by a change in water-surface profile, even after the transients initially induced by the change have dissipated. The resulting changes in volume of water within the canal can be influenced by exercising the gates or other control structures. In any event, whatever the change in volume induced by new flow conditions, a finite time is required for a mismatch in inflow and outflow to produce it. This time is related to the time to establish the new conditions. Thus, even the study of a succession of steady states is useful in predicting the response time of a canal to changes in regime. Experiential evidence indicates that such predictions constitute an approximation to transient canal response as well. Comparisons of results based on the simplified steady-state theory with those based on the full Saint Venant equations of unsteady flow should delineate the degree of approximation as a function of canal properties and the timing of imposed transients.

An experimental, generic model of unsteady flow is used in the study instead of existing industrial models because of the flexibility in internal and external conditions afforded by the custom model and to allow input and output in dimensionless terms. This means referencing all discharges to an initial steady-state flow rate, all transverse dimensions (depth, width, elevation, etc.) to normal depth at the reference discharge, all longitudinal lengths to normal depth divided by bottom slope, and all times to a reference time equal to the time to traverse the reference length at normal velocity. In this way, a broad range of canal parameters--base width, side slopes, bottom slope, roughness, length, gate openings, and initial discharge--can be covered without calling for an inordinate amount of experimentation and complexity in presenting results.

The method of characteristics was selected as the solution mode for transient flows because of its theoretical correctness and its potential for disclosing facets of flow behavior that could be missed by more approximate schemes. While the model cannot as yet simulate flow after formation of a bore, this condition is not common, and since calculation stops at the computed inception of a bore and an alert printed, there is no danger of spurious computations. The numerical solution scheme serves as a subroutine to a calling program that automatically varies dimensionless input parameters over given ranges. Select measures of canal response are output to a file, one record per simulation. After an appropriate group of simulations has been run (perhaps several hundred), the data from the output file are analyzed and plotted by a separate stand-alone program.

FINDINGS: Curves characteristic of possible steady states in a canal pool have been constructed on the basis of checked-up water-surface profiles behind control gates, calculated at various flow rates. These show pool volume as a function

of flow rate and checked-up depth. Figure 1, constructed for a particular pool geometry, shows how operation of the pool to maintain a constant downstream depth in spite of a 6 $m^3/sec$ change in flow rate (vector $A$) requires the addition of 21000 $m^3$ to the pool (about 1 hour at $6m^3/s$). Vector $B$ depicts a *constant-volume* operation achieved by adjusting the gates to yield a downstream depth change of -0.15 $m$.

Typical unsteady pool response to a sudden increase in the flow of a downstream offtake under conditions of "ideal control" without anticipation of flow changes, i.e., simultaneous, exact replacement of the offtake discharge at the upstream end, is displayed in figure 2. In this scenario, with the gate opening fixed, the offtake withdrawal takes place at the expense of pool volume until the replacements initiated simultaneously at the upstream end arrive. The wave motion generated by the offtake results in a drawdown in depth there (offtake flow, for simplicity, is assumed fixed, as if pumped). The curves, for a broad range of hydraulic conditions, and withdrawal of 60% of the initial flow, show maximum depth reduction in ratio to initial depth.

Figures 3 and 4 show the results of a different scenario. Here, in anticipation of downstream withdrawals, a 10% step increase in flow is initiated at the upstream end of a pool. In consequence of the canal-pool hydraulics, the step is smeared over time (and with distance, as the wave propagates into the pool) to result in the flow hydrographs shown for the end points and quarter points along the length. Smearing, the deformation of the supply wave from a step to a ramp, is shown by the time delay between the arrival of the beginning of the wave, corresponding, say, to 10% of the total step change, and that of the bulk of the wave, say, characterized by the 85% point. The extent of the smearing depends upon distance from the upstream end and somewhat on the Froude number of the flow; it is heavily dependent on the specific downstream-boundary structure. Figure 3 compares the canal response for three downstream boundary conditions: 1) a submerged, undershot gate, very common in canals, 2) normal depth, a theoretical condition corresponding to a long length of prismatic canal downstream from the subject reach, and 3) a long-crested (duck bill) weir designed to pass small or large flows with little change in head. Figure 4 quantifies the functional dependence for a pool of rectangular cross section, initially checked up to 1.25 times normal depth.

INTERPRETATION: Steady-state analysis yields important results, valid for at least the end points of a transitory phenomenon. Its applicability during the period of the transient remains under investigation.

Unsteady-flow analysis shows that even under conditions of perfect control, replacing offtake demands with upstream flow increases takes time, and that until the replenishments arrive in sufficient quantity, the depth at the offtake continues to fall. The longer the canal, the greater the offtake, and the greater the Froude number of the initial uniform flow, the greater is the maximum drawdown. Curves such as in figure 2 quantify the behavior and can show when *anticipatory* regulation is mandatory, to prevent excessive drawdown.

Figures 3 and 4 highlight the overriding influence of the downstream stage-discharge relationship on supply-wave deformation. Further, they quantify the expected effect of pool length and the relatively minor influence of Froude number. The toe of the wave arrives at about the same time with each different downstream structure, while the bulk of the wave (85% of the total upstream step change) arrives significantly later for the gate than for the weir. Much of this delay can be viewed as a response to the higher depths of flow (and hence greater pool volumes) required to pass the increased discharge through the gate opening than over the long-crested weir. This supports the use of such weirs as control structures.

FUTURE PLANS: Canal response to additional control scenarios will be investigated, including a specified inline outflow hydrograph. The steady-state approach exemplified in figure 1 will be compared to analyses explicitly treating the unsteadiness. The ranges of parameters in ideal-control and anticipatory-step-increase scenarios will be extended.

For comparison with the method of characteristics, the generic canal model will be extended to include additional control-structure elements and upstream and downstream boundary conditions and multiple pools, as well as an implicit, fixed-grid numerical solution scheme common in industrial models. Simulating additional regimes of flow behavior, such as supercritical flow and bore propagation, will also be investigated.

**COOPERATORS: Jean-Luc Deltour, GERSAR-SCP, Societe du Canal du Provence, Aix-en Provence, France; Charles Burt, California Polytechnic State University, San Luis Obispo, CA.**

## INVERSE COMPUTATIONAL METHODS FOR OPEN-CHANNEL FLOW CONTROL

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and T.S. Strelkoff, Research Hydraulic Engineer

PROBLEM: Gate stroking (Wylie, 1969; Falvey and Luning, 1979) is one of several methodologies currently available for regulating open-channel flows. The objective of the method is to determine the operational schedule for the canal's control structures that will deliver a predetermined demand schedule. The algorithm is based on solution of the equations of unsteady open-channel flow. In contrast with typical routing simulations, which begin at an initial time and proceed forward in time, gate-stroking computations begin at the downstream boundary of a canal pool, where the demand is specified, and then move upstream (i.e., backward in the space direction) until reaching the canal's upper boundary. Thus, gate-stroking is also known as inverse open-channel flow computation. Implementation of the method requires prior knowledge of the demand schedule and central control of the regulating structures.

The gate-stroking approach has found limited application in the field due to practical constraints. Still, the method is valuable in that it can be used to analyze the control requirements of a delivery system under different operational scenarios. Surprisingly, it has not been used extensively for this purpose, perhaps because of its mathematical complexity. Wylie's (1969) and Falvey and Luning's (1979) gate-stroking solutions are based on the method of characteristics and are computationally delicate. Finite-difference solutions of the open-channel flow equations are potentially more robust than characteristics solution and, thus, several authors have tested their application to the gate-stroking problem. In 1994, a study was initiated to compare two finite-difference inverse algorithms, one implicit (Chevereau, 1991) and the other explicit (Liu et al. 1992), with the method-of-characteristics solution. The objective of the work is to identify an inverse algorithm that can be used reliably under a wide range of control scenarios and to use the model to study the controllability of open-channel water delivery systems.

APPROACH: Studies on the controllability of canals have focused on understanding how transient waves created by upstream or downstream disturbances behave in time. This type of analysis requires multiple simulations with a conventional routing model. A related problem, illustrated in figure 1, is to characterize the magnitude of the upstream disturbance (dotted lines) that needs to be applied at upstream control points (e.g., gate structures) in order to achieve a given change in downstream canal supply (solid line). Upstream hydrograph features of interest include the peak depth and discharge and the duration of the transient. This problem can be studied by performing multiple simulations with a gate-stroking model.

Tests conducted during 1994 showed the limitations of the existing finite-difference and characteristics-based gate-stroking algorithms (Bautista et al. 1995). Based on the approach presented by Chevereau (1991), an implicit nonlinear finite-difference gate-stroking solution was proposed (Bautista et al. 1995). Additional tests were conducted in 1995 with the improved model and, in view of the positive results, it was selected as a basis for conducting a study on canal controllability. Given the relatively slow performance of the available computer code and the large number of simulations that will be eventually conducted, the code was translated to a faster programming language. To further reduce the computational effort, the number of design parameters needed in the study was reduced by adopting a nondimensional formulation of the governing equations.

FINDINGS Solutions computed with the nonlinear implicit finite-difference model showed that it is nearly as accurate and more robust than the characteristics-based model. The upstream hydrographs computed with the finite-difference model can exhibit some numerical damping for very rapid changes in demand in comparison with the characteristics solutions (i.e., the characteristics-generated hydrographs show sharper peaks). However, when the solutions produced by either model are fed back into a forward simulation model, the resulting downstream hydrographs are far more similar than the upstream discharge hydrographs. Since gate-stroking solutions usually can not be implemented exactly in the field, the damping introduced by the finite-difference algorithm will likely not compromise the usefulness of the gate-stroking solutions.

The type of canal relationships that are being studied is illustrated next. Figure 2 shows the specified demand hydrograph for a canal pool with particular nondimensional characteristics. The dimensionless system of variables used is described in Strelkoff and Clemmens (1995). In that system, depth is expressed relative to normal depth $Y_n$ for the given design inflow $Q_n$, while velocity is expressed relative to $V_n$, the normal velocity. With these definitions, the dimensionless depth and velocity at normal flow, $Y_n^*$ and $V_n^*$, respectively, are both equal to one. If the canal cross-

section is trapezoidal, it follows that the dimensionless normal area $A_n^* = Q_n^* = b^* + z$ , with $b^*$ the dimensionless bottom width and z the side slope (H/V). For canals of uniform slope $S_0$ and Manning roughness n, their dimensionless equivalents are equal to unity. A family of hydraulically similar canals is then defined by the particular combination of dimensionless variables $b^*$, z, canal length $L^*$, and $F_n$, the Froude number at normal depth for the design inflow. For the example, we set $b^*$, z, and $L^*$ to 2, 1.5, and 0.5, respectively, and allowed $F_n$ to vary. The dimensionless discharge $Q^*$ was increased stepwise from its initial value, $Q_n^* = 3.5$, by 10% at dimensionless time $T^* = 1.0$. Backwater conditions were imposed on the example by fixing the dimensionless depth $Y^*$ at the downstream boundary at a value of $1.2Y_n^*$. Figures 3 and 4 show the upstream discharge and depth hydrographs computed for three subcritical values of $F_n$. Hydrograph characteristics change dramatically as $F_n$ increases from $F_n = 0.1$ to $F_n = 0.4$, but changes are less conspicuous at higher Froude numbers. Note in particular that peak $Q^*$ and $Y^*$ decrease with increasing $F_n$, while the duration of the transient (i.e., the time between the initial and final change in upstream $Q^*$) increases. Note also that for $F_n \geq 0.4$, the peak upstream $Q^*$ is essentially equal to the desired final demand, $Q^* = 3.85$.

**INTERPRETATION:** The results given above are an example of the type of relationships that can be studied using the gate-stroking model expressed in nondimensional form. For canals sharing the given geometric configuration subject to hydraulically similar demand hydrographs, upstream disturbances will undergo substantial attenuation as they propagate downstream if $F_n < 0.4$; for larger subcritical values of $F_n$ wave deformation and diffusion will be far less significant. This implies that for $F_n \geq 0.4$, the prescribed demand hydrograph can be satisfied adequately with this family of canals by imposing an identical upstream inflow hydrograph shifted by a time delay factor $\Delta T^*$. This delay factor is related to $L^*$ and some average wave propagation velocity. Preliminary results indicate that the propagation velocity can be satisfactorily estimated from kinematic wave theory, i.e., $dX^*/dT^* = dQ^*/dA^*$ for $0.4 \leq F_n \leq 0.7$, but that for larger $F_n$, a better estimate is provided by the dimensionless dynamic wave velocity, $dX^*/dT^* = V^*(X^*, T^*) + C^*(X^*, T^*)$, in which $X^*$ and $C^*$ are the dimensionless distance and wave celerity, respectively. Approximate analytical values for the delay factor are $\Delta T^* \approx 0.35$ for $F_n = 0.4$ and $\Delta T^* \approx 0.22$ for $F_n = 0.9$.

A difficulty in the interpretation of the results is that their meaning in dimensional form is not immediately obvious. For the particular example, if one assumes a base width of 2 meters and a Manning n of 0.2, for the range of $F_n$ values studied, the data represent a flow-rate range from 5.2 to 46.7 $m^3/s$, slopes ranging from $4 \times 10^{-5}$ to $3.4 \times 10^{-3}$, and lengths from 24.5 Km to 0.3 Km.

**FUTURE PLANS:** A large number of dimensionless variable combinations needs to be tested before generalized results can be developed. Ranges of the design variables to analyze are currently being defined. The above presented results have focused on the relationship between $F_n$ and peak $Q^*$ and $Y^*$; however, it is expected that other relevant relationships will emerge as the study progresses. Modifications to the model are currently underway to add batch-file mode operation capabilities, as multiple executions will be required. The initial effort will concentrate on analyzing the response of single pool canals. The general properties of the gate-stroking solution for multiple-pool canals will be studied later.

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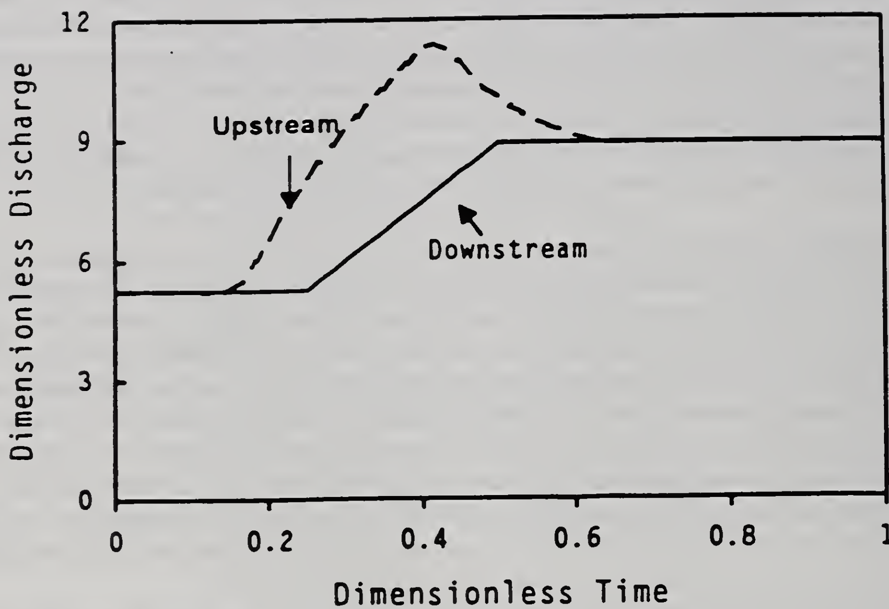


Figure 1. Variation in upstream inflow rate needed to deliver a predefined downstream demand.

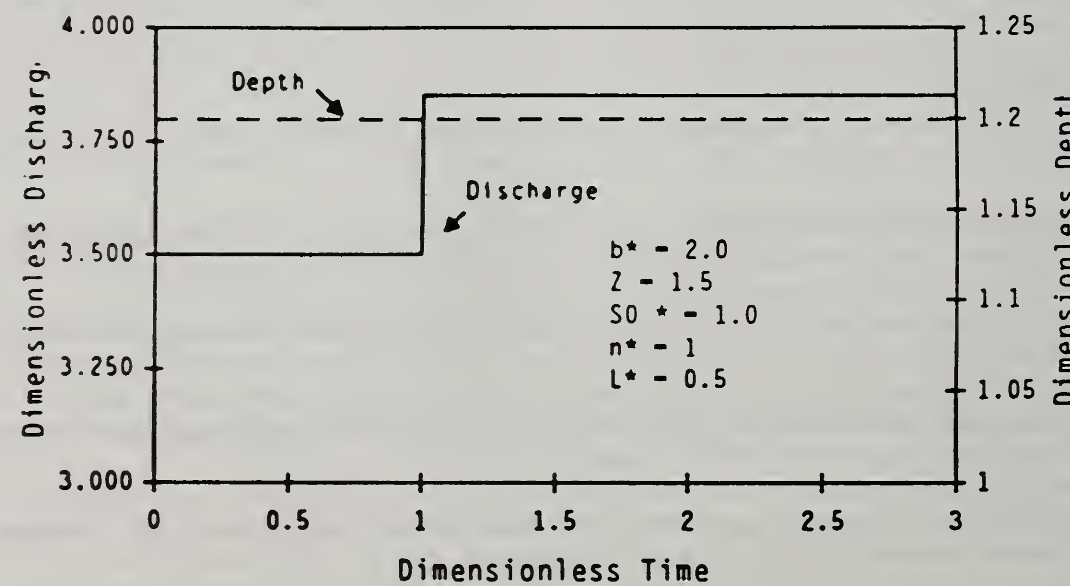


Figure 2. Specified downstream discharge and depth hydrographs for the example problem.

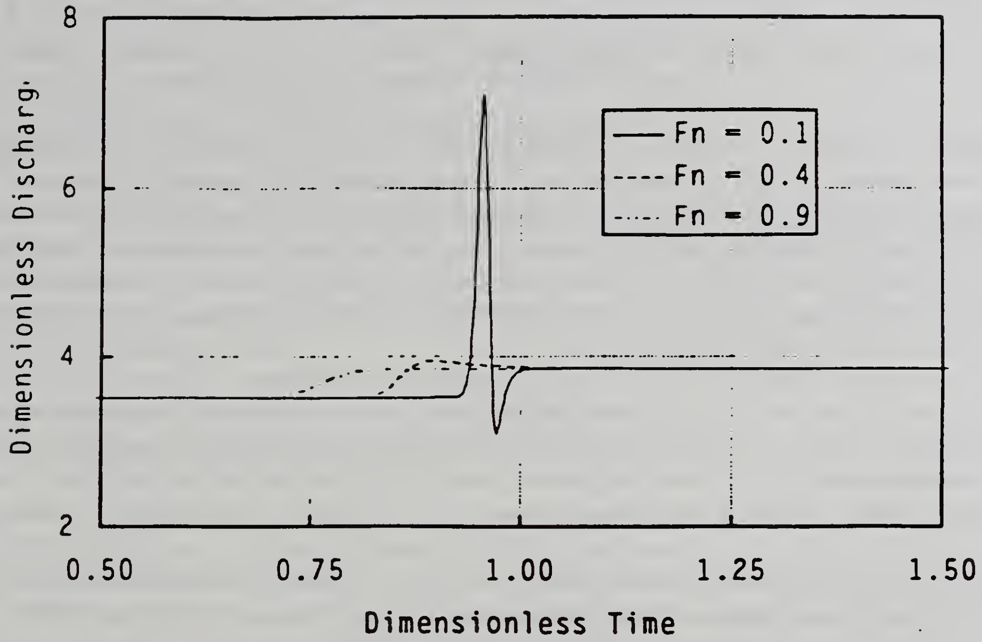


Figure 3. Upstream discharge hydrographs computed with increasing Froude numbers.

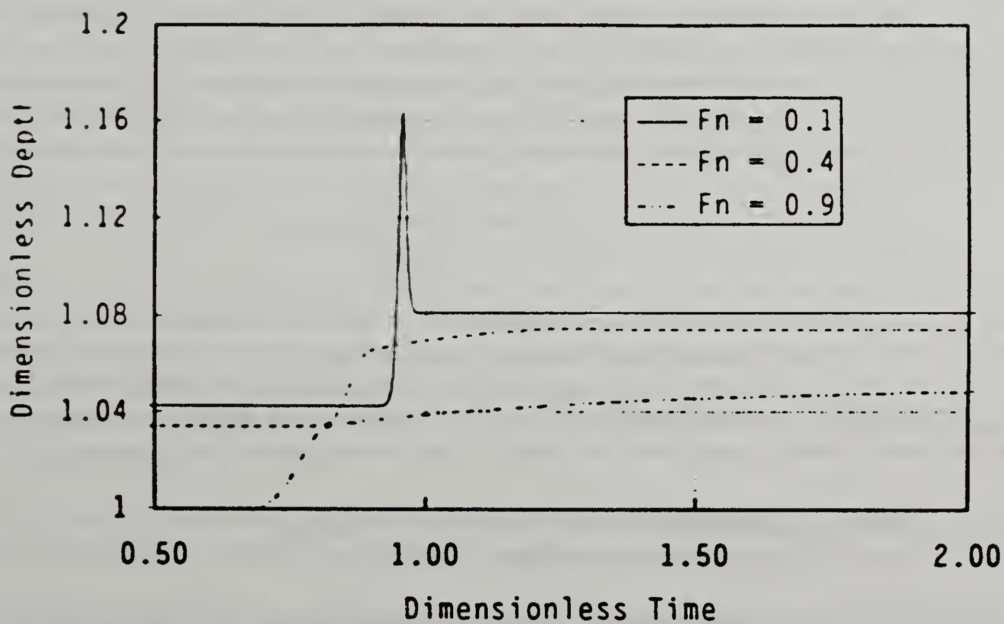


Figure 4. Upstream depth hydrographs computed with increasing Froude number.

# DEFINING IRRIGATION SYSTEM PERFORMANCE

A.J. Clemmens, Supervisory Research Hydraulic Engineer;
and T.S. Strelkoff, Research Hydraulic Engineer

**PROBLEM:** High water costs and the potential for environmental degradation, as well as intense competition for a limited water resource prompts growers' concern for water conservation in addition to the traditional concerns of crop yield and quality. With irrigation often constituting the largest portion of a region's water consumption, and competing users often in a political majority, the need for sagacious use of irrigation water becomes paramount. Users of irrigation water are frequently confronted with the need to defend their share of the water resource with the argument that it is necessary and is wisely used. Different irrigation methods - e.g., surface, sprinkler, micro—need to be compared in terms of water consumption as well as other factors.

Under the present plethora of concepts, terms, and ad hoc definitions, different agencies have calculated widely disparate numbers for terms of the same name. For numerical characterizations of irrigation-system performance to have universal meaning, unique and consistent definitions of efficiencies, uniformities, and other performance indicators are required, broadly applicable to different irrigation systems, to different subject regions—field, farm, district, basin, etc., over different periods of time—a single event, a season, etc., and both on the drawing board and in the field.

**APPROACH:** A Task Committee was formed by the On-Farm Committee, WRE Division, ASCE, and charged with proposing appropriate definitions, to the Society and to the profession. The authors of this report and their listed cooperators were heavily involved in drafting the proposed definitions.

A point of departure was provided by an earlier (1978) On-Farm Irrigation Committee in a well known, concise paper on uniformity and efficiency. Its very conciseness, however, has led to ambiguity in implementation. The Task Committee reviewed the basic concepts introduced therein and sharpened or replaced, as necessary, the definitions of performance in the light of different possible applications (as enumerated above) and, especially, in explicit recognition of extant nonuniform application of irrigation water. Also recognized was the need for precise specification of the region and time interval implied in a definition, the need for defensible, rather than intuitive, procedures for establishing parameters, and the need for evaluating defensible measures of confidence in any of the derived parameter values.

**FINDINGS:** Irrigation Efficiency: Efficiency is based on the identification of the various fractions of the irrigation water supplied to a subject area. The definitions concern only water supplied by irrigation, however difficult it is to exclude natural contributions—precipitation, groundwater influx, etc.—from a total water balance. Water that leaves the subject area through its boundaries can be categorized as beneficial *to the crop* (or else, reasonably, or consumptively used) or not. Any water temporarily stored within the boundaries cannot be so categorized, even if intended for a beneficial use, say the next crop; it must be considered neutral until it actually leaves in one or another category. Example boundaries are the soil surface and bottom of the root zone along with a definition of areal extent.

*Irrigation efficiency*, *IE*, is defined within specified boundaries and over a specified time interval, as the ratio of water volume beneficially used, to the volume that left the subject area, both during the specified period, i.e.,

$$IE = \frac{\textit{volume of irrigation water beneficially used}}{\textit{volume of irrigation water applied} - \Delta\ \textit{storage}} \times 100\% \tag{1}$$

in which $\Delta$ *storage* is the change in storage of irrigation water within the subject region over the specified time interval. Water serving a dual purpose (e.g., both frost protection and seed germination) is not to be double counted. Beneficial use is not to be confused with consumptive use. Figure 1 illustrates the difference. It also provides the basis for establishing an *Irrigation Consumptive Use Coefficient*, *ICUC*, defined as the ratio between the volume of irrigation water consumed (evapotranspiration, plant tissue, etc.) and the total volume that has left the region, both in a specified period of time,

$$ICUC = \frac{\textit{volume of irrigation water consumptively used}}{\textit{volume of irrigation water applied} - \Delta\ \textit{storage}} \times 100\% \tag{2}$$

Like *IE*, *ICUC* can be used on any geographic scale. At the district scale, e.g., the total district outflow of irrigation water in the specified period is (100 - *ICUC*)% of the irrigation water supplied.

From the societal and even a grower's point of view, *IE* alone may not be sufficient to characterize water use. Other

benefits can accrue to society from water used for irrigation, even a portion not used by the crop, for example to support riparian wildlife. Or, it may well be prudent for a grower to apply some water that is *not* directly used by the crop, i.e., unavoidable nonbeneficial uses. Such concepts of *reasonable use* suggest a new term to complement irrigation efficiency, namely, irrigation sagacity, IS,

$$IS = \frac{\text{volume of irrigation water beneficially and reasonably used}}{\text{volume of irrigation water applied} - \Delta \text{ storage}} \times 100\% \tag{3}$$

**Application Efficiency:** For planning purposes, or to judge performance of a system in the field, efficiency revolves not around actual plant needs, but around how well the system satisfies a perceived need. *Application Efficiency, AE,* is based on the concept of a crop *requirement* for that irrigation. The chosen required depth may be the soil-moisture deficit *SMD*, or some smaller amount, say, to accommodate potential rainfall; it may contain a required *leaching fraction*, or it may simply be a typical target irrigation depth. Thus

$$AE = \frac{\text{volume of irrigation water contributing to the requirement}}{\text{volume of irrigation water applied}} \times 100\% \tag{4}$$

A stated requirement eliminates the necessity for specifying a time period in the definition. If the requirement is just equal to the sum of the expected beneficial uses, application efficiency provides an estimate for the potential irrigation efficiency (i.e., what the *IE* will be if the expected benefits occur, and if the beneficial uses are uniform over the field).

**Potential application efficiency:** With the assumption that the specified irrigation requirement is just met by the low-quarter depth $d_{lq}$, the *potential application efficiency* of the low quarter, $PAE_{lq}$, is given by

$$PAE_{lq} = \frac{\text{volume of irrigation water contributing to requirement}}{\text{volume of irrigation water applied such that } d_{lq} = \text{requirement}} \times 100\% \tag{5}$$

For a given system, this is of particular value in providing an estimate for the gross amount of water to apply. With the distribution shape more-or-less fixed, it provides minimal underirrigation, minimal excess deep percolation, and minimal runoff.

Adequacy, $AD_{lq}$: It is possible to attain a very high *AE* in a field by underirrigating. A complementary parameter indicating the degree to which the *requirement* $d_{rlq}$ *is met* is, thus, also a pertinent performance parameter. *Adequacy* based on a requirement to be satisfied by the low-quarter depth $d_{lq}$ is defined by

$$AD_{lq} = \frac{d_{lq}}{d_{rlq}} \tag{6}$$

If low-quarter depth is used as the scheduling criterion, then proper irrigation duration corresponds to $AD_{lq} = 1.0$, with about 1/8th of the field underirrigated. Adoption of the criterion, $AD_{lq} = 1.0$, targets the average low-quarter depth rather than the absolute minimum. Table 1 highlights the significance of different values of $AD_{lq}$.

**Deep Percolation** is defined as that water in excess of leaching needs that penetrates beyond the root zone. Because of nonuniform application, there can be nonbeneficial deep percolation even if, in some portions of the subject area, neither leaching, nor soil-moisture deficit is satisfied (see fig. 2).

INTERPRETATION: Consumptive Use and Irrigation Efficiency and Sagacity have no meaning except in the context of both a given time interval and a given spatial region of application. Application efficiency, however, by substituting a perceived need for actual benefits, is event based and is not associated with any particular time interval. The potential application efficiency is realized when the Adequacy of irrigation is just unity.

Universal adoption of precise terminology can do much to bring order and equity into water allocation and management decisions.

**FUTURE PLANS: A series of papers documenting various phases of the Task Committee's work will be published. The ensuing dialogue in the Society and the profession should lead to a consensus.**

COOPERATORS: Charles Burt, Calif. Polytechnic State University, San Luis Obispo, CA; Kenneth H. Solomon, California State University, Fresno, CA.

Table 1. Significance of $AD_{lq}$

| Characterization of irrigation duration | Values of $AD_{lq}$ |
|---|---|
| Underirrigation | $AD_{lq} < 1.0$ |
| Proper | $AD_{lq} = 1.0$<br>$AE = PAE_{lq}$ if surface losses match potential values |
| Overirrigation | $AD_{lq} > 1.0$ |

# TECHNOLOGY FOR IMPROVED MANAGEMENT OF IRRIGATED AGRICULTURE

# IRRIGATION FLOW MEASUREMENT STUDIES IN CLOSED PIPE SYSTEMS

J.A. Replogle, Research Hydraulic Engineer; and B.T. Wahlin, Civil Engineer

**PROBLEM:** Propeller meters and end-cap orifices are well established flow measurement devices for closed pipe systems. However, both devices have some major drawbacks. Propeller meters tend to become clogged in debris-laden flows. As a result, propeller meters are usually inserted into trashy flows for only a short period of time to get just a sample measurement, and then they are removed. Problems with end-cap orifices arise from the pressure taps used to detect the head. A flange tap is located in an area of high velocity gradients and can lead to unstable head readings. Pressure taps located upstream of the orifice introduce a permanent hole in the pipe wall and raise questions on whether the tap is truly free of burrs. Improving the propeller meter's ability to shed trash and using the head detection method for end-cap orifices would make it a more useful flow measurement device.

**APPROACH:** Propeller meters for trash-filled flows were constructed by suspending swept-back (conical) propellers by their point instead of holding them in place from behind (fig. 1). The front-holding brace was shaped to push the trash down and away from the spinning propeller. A standard propeller meter gears the propeller to a totalizer device that can then report the total volume applied or flow rate in the desired units. These mechanical gear systems can cause additional drag on the propeller and lead to premature failure of the meter. The mechanical gear systems of standard propellers were eliminated in favor of magnetic pick-up methods to reduce the chance of failure.

An alternate pressure tapping system for the end-cap orifice using a small static Pitot tube (with holes drilled through its walls) to detect the pressure in the large pipe upstream of the orifice was studied (fig. 2). The tube was inserted through a grommet-sealed hole in the face of the orifice plate near the pipe wall. The Pitot sensing holes were placed one pipe diameter upstream of the face of the orifice plate.

**FINDINGS:** Laboratory and field tests on a prototype of the trash resistant propeller meter have been completed. The propeller meter could shed most of the trash that came through the pipe. The only things that the meter was not able to pass regularly were long, stringy items such as long pieces of surveying ribbon. These items tended to get caught in the spinning propeller blades before the front brace could push them away. Negotiations were successful with Global Water, a meter builder in Fair Oaks, California, to construct industrial prototypes of the trash resistant propeller meter.

The calibration of the end-cap orifice using both flange taps and upstream pipe taps was verified using the laboratory weigh-tank system (fig. 3). The University of Arizona provided a comparison for the flange tap calibration while the Natural Resource Conservation Service provided a comparison calibration for the pipe taps. The static Pitot tube was placed in pipe about 1/4 of an inch away from the wall. This distance was close enough to the wall so that trash did not become stuck on the tube and far enough away from the wall so that the wall did not affect the head reading. The method of readout based on the static Pitot was confirmed to be viable.

**INTERPRETATIONS:** Prototypes of the trash resistant propeller meters from Global Water are expected in the spring of 1996. These meters will use a battery-powered computer to display the current flow rate and total flow in any units and for all pipe diameters. The meter will consist of a 10-inch diameter propeller that rotates freely on a stainless steel shaft. The trash resistant propeller meter will eliminate the need for operators constantly to monitor the propeller meter when it is being used in trashy flows. Instead of being able to have the meter in a debris-laden flow for only short time periods, users can leave the meter in the flow for extended periods of time without worrying about whether or not the meter will clog.

Implementation of the static Pitot tube for field use in an end-cap orifice appears easy to do. This arrangement removes the uncertainty of a flange tap and does not create the inconvenience and uncertainty of drilling into the existing pipe walls.

**FUTURE PLANS:** The first industrial prototype of the trash resistant propeller meter will be delivered in the spring of 1996. Extensive laboratory and field tests will be performed to verify the meter's ruggedness and trash-shedding ability. To make the laboratory tests as similar to field conditions as possible, the laboratory plumbing is being modified to accept large concrete pipes supplied by the Salt River Project. The Wellton-Mohawk Irrigation and Drainage District will provide propeller meter wall brackets and assist in coordinating field tests within the district.

Field-use verification of the end-cap orifice will also be conducted. Initially, field tests will be performed at the Maricopa Agricultural Center. Later, additional field tests will be performed in cooperation with the Maricopa-Stanfield Irrigation and Drainage District.

**COOPERATORS:** Salt River Project, Charles Slocum of the Wellton-Mohawk Irrigation and Drainage District, Maricopa-Stanfield Irrigation and Drainage District, and John Dickerman of Global Water.

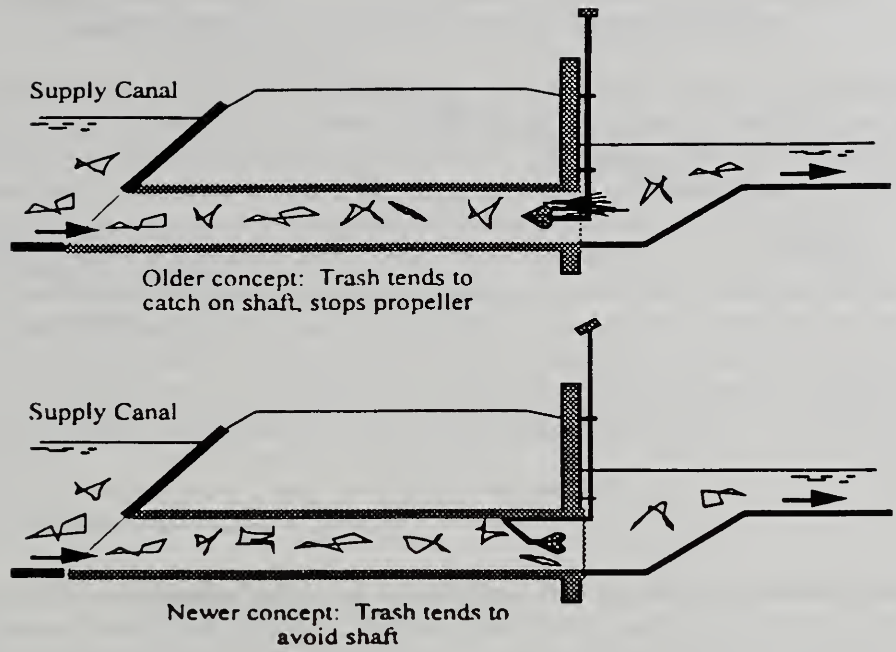


Figure 1. Weed resistant propeller meter.

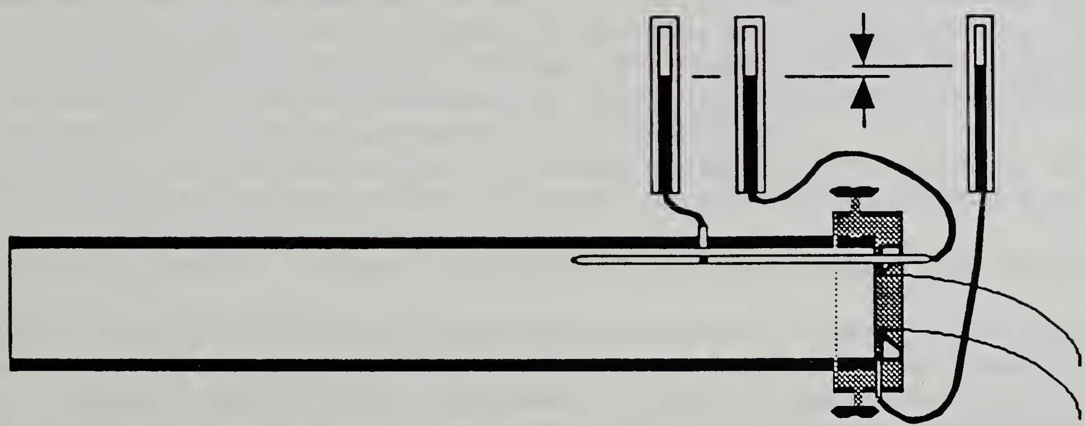

Figure 2. Static Pitot probe and wall pressure tap produce similar results.

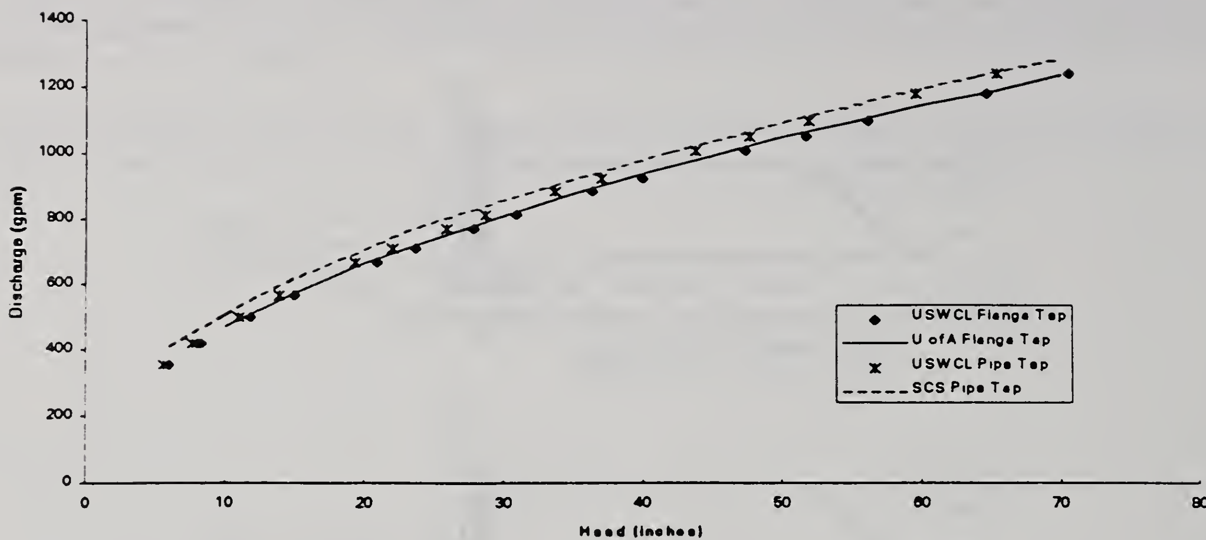


Figure 3. Comparison of USWCL end-cap orifice calibrations to existing calibrations.

# IRRIGATION FLOW MEASUREMENT STUDIES IN OPEN CHANNEL SYSTEMS

J.A. Replogle, Research Hydraulic Engineer; B.T. Wahlin, Civil Engineer;
and A.J. Clemmens, Supervisory Research Hydraulic Engineer

**PROBLEM:** Parshall flumes have been popular flow measurement devices for open channels since their introduction in 1926. Traditionally, problems have arisen in Parshall flumes if they are operated under highly submerged conditions or if they are not constructed exactly to Parshall's specifications. Also, the U.S. Bureau of Reclamation has recently noted a range of submergence in which two values of discharge can occur for the same submergence ratio and upstream head. These problems have rendered many existing Parshall flumes almost useless. It is desirable to have a method to modify a wrongly constructed or overly submerged Parshall flume to recover some of its function.

Broad-crested weirs are attractive for open channel flow measurement because of their high accuracy, low cost, ease of construction, and ability to handle high degrees of submergence. One of the most important factors in designing a broad-crested weir is vertical placement of the sill. If the sill is too low, then the flume may become flooded out and loose its function. If the sill is too high, on the other hand, there may be an inadequate amount of freeboard upstream of the flume. If a single, portable broad-crested weir is to handle a wide range of flow rates and flow conditions, then it must have an adjustable sill.

While the FLUME program has been widely used, bugs continue to show up. Also, the program graphics are sometimes poor and control of printed output is difficult.

**APPROACH:** The historical calibration of a one-foot Parshall flume was verified under both free flow and submerged conditions using the laboratory weight tank system. A false concrete bottom was then placed in the throat of the Parshall flume to convert it into a computable long-throated flume (fig. 1). The standard stilling well reading point was preserved.

To encourage commercialization of the portable long-throated flume with an adjustable sill, advice was offered to an interested company. Most of the advice concerned manufacturing methods and materials, their effects on calibration accuracy, if any, and laboratory verification of a pre-production prototype.

Work continues correcting the bugs within the FLUME program. An updated version has been planned by the International Institute for Land Reclamation and Improvement (ILRI) in The Netherlands but not funded.

**FINDINGS:** A one-foot fiberglass Parshall flume was installed for study in the laboratory. The unmodified Parshall flume was calibrated under free-flow conditions using the laboratory weigh-tank system. The historically reported calibration of the 1-foot Parshall flume was reproduced to within $\pm 2\%$ after adding flow straighteners upstream from the approach section of the flume. The Parshall flume was also calibrated under submerged conditions, and the anomalous submergence behavior noted by the U.S. Bureau of Reclamation was verified. The modified Parshall flume behaved as predicted by long-throated flume theory without modifying the upstream sensing location.

Laboratory testing of the pre-production prototype of the adjustable sill, long-throated flume confirmed the ability of the computer model to predict the flow calibration accurately. Calibrations were performed on the adjustable flume with sill heights of 2, 4, 5.5, 7.5, and 8.5 inches.

The FLUME calculations for backwater levels based on user input of flows and water levels have finally been fixed.

**INTERPRETATIONS:** The ability to modify Parshall flumes to behave as computable long-throated flumes opens the way to recover function of wrongly constructed or overly-submerged Parshall flumes. Measuring discharge using a Parshall flume under submerged conditions requires two head readings. Treating the Parshall flume as a long-throated flume removes the need for a second head reading. Also, the modification removes the anomalous submerged behavior noted by the U.S. Bureau of Reclamation on the 1-foot Parshall flume.

Vertical placement is one of the most important field decisions for installing long-throated flumes and must be competently supervised to avoid costly refitting or improper function. The development of an adjustable sill long-throated flume nearly eliminates this problem for the farm irrigation user. Also, if the flow conditions change after the flume has been installed, the sill can be simply raised or lowered to make the flume operate properly instead of digging out the flume and reinstalling it at a different level.

A few short courses on irrigation flow measurement were conducted during the year. These courses were well received and may be conducted on a recurring basis. Because of these courses, irrigation districts change their methods of operation in favor of suggested approaches that are more economical and effective than previous concepts. A number of

book chapters were also written during the year. These book chapters can positively influence irrigation flow metering and contribute to water resources functions well into the next century. The book chapters were:

- *Handbook of Water Resources*, Part III, Water Resources Supply, III.22 Irrigation Systems. Replogle, Clemmens, Jensen. Editor: Larry Mays (at publishers).
- *Water Measurement Manual: A Water Resources Technical Publication*, U.S. Bureau of Reclamation. In cooperation with the Manual Revision Team (to USBR Editors).
- *Operation and Design of Farm Irrigation Systems*. Editors: M. Jensen and R. Elliott. Revision and consolidation of Chapters 9 and 11. J. Replogle, ARS; and G. Kruse, ARS. (Draft to Editors).
- Sub-Chapter (Part of Chapter 2) "Measurement of Streamflow." *Handbook of Hydrology*. American Society of Civil Engineers. Replogle, ARS; and Riggs, USGS. (Still awaiting editors review).
- Short Course participation: Lectured at the Mexican Institute of Water Technology (IMTA) and at a Short Course sponsored by Texas Extension Personnel, El Paso.
- Advice to USBR, Grand Junction, on flow measuring structures to be constructed throughout the local irrigation district distribution system.

FUTURE PLANS: A 4:1 scaled-down model of an 8-foot Parshall flume will be calibrated, modified, and evaluated. Because Parshall flumes are not geometrically similar, the model of a large Parshall flume will have a much different proportional shape than a standard 1-foot Parshall flume.

A potential manufacturer of an adjustable flume appears ready to market the models for 2,4, and 6 cfs maximum flows by March 1996 under the name "Adjust-a-Flume."

An idea for a sediment resistant flume system that combines critical-flow and supercritical-flow flumes for measuring heavily sediment-laden flows has been temporarily suspended pending available setup space in the hydraulics laboratory.

The new DACL valve reported last year will be evaluated for controlling irrigation gate flows to an adjustable constant rate. Testing will evaluate function and durability.

COOPERATORS: Brent Mefford of the U.S. Bureau of Reclamation, Charles Overbay an industrialist, Rien Bos of ILRI, and Jan Groenestein of Groenestein en Borst vof, The Netherlands.

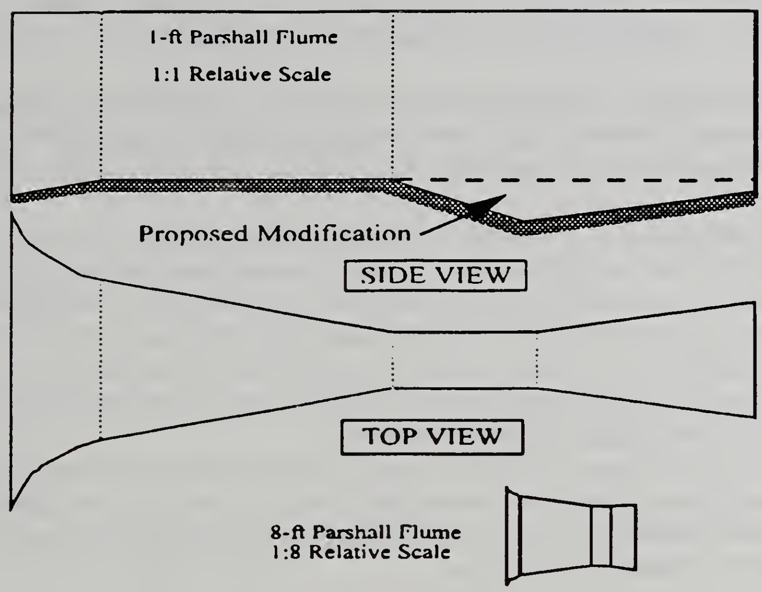


Figure 1. Parshall Flumes showing the tested modification and the large proportional differences between a 1-ft model and an 8-ft model (scaled to have the same width).

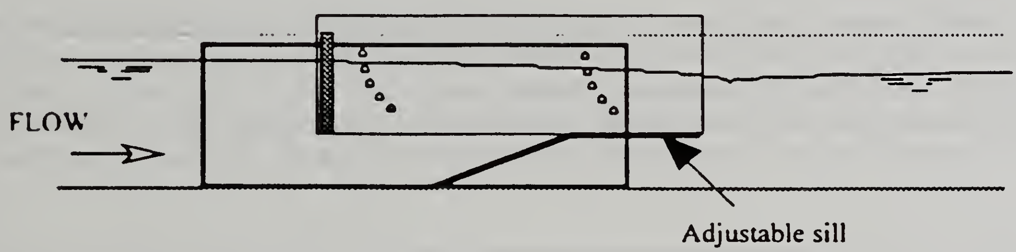


Figure 2. Long-throated flume with an adjustable sill.

# MODIFIED LEAF GATES FOR CANAL CONTROL AND FLOW MEASUREMENT

B.T. Wahlin, Civil Engineer; J.A. Replogle, Research Hydraulic Engineer;
and T.S. Strelkoff, Research Hydraulic Engineer

**PROBLEM:** Recently, overshot gates, or leaf gates as they are sometimes called, are becoming increasingly popular for controlling water levels in open channels (fig. 1). This popularity is partly due to the ability of the gates to handle flow surges with limited depth changes and the ease with which operators can understand the hydraulic behavior of the gates.

The main purpose of most control gates is to maintain a constant water depth upstream so that orifice-based offtakes, usually located just upstream of the gates, can deliver water at a near-constant rate regardless of the flow rate in the main canal. The control gates themselves can either be orifice-based gates, such as sluice or radial gates, or weir-type gates. Overshot gates combine the best aspects of both sharp-crested weirs and orifice control gates. With one of these gates, the water level can be controlled with the accuracy of a sharp-crested weir, and the gate can be adjusted with the ease of an orifice gate. Overshot gates also require less intuitive calculation in their operation because a 10-cm drop in gate height corresponds closely to a 10-cm drop in upstream water level.

While water level control is useful, operators also need to know the flow rate at each gate in many cases. Recently, empirical discharge equations for both free-flow and submerged conditions have been developed for the overshot gate. While these results have already assisted operators in determining the flow rate over the gates, it is still desirable to compare these empirical results to theoretical predictions.

**APPROACH:** Free-surface flows over weirs are extremely difficult to calculate because of the influence of gravity on the free-surface configuration. Analytical solutions for these types of problems do not exist, and solutions must be obtained numerically. Dias and Tuck (1991) have recently presented a method in which two-dimensional free-surface flows over vertical and inclined weirs can be computed numerically. This method describes the upper and lower nappes through a series of grid points, and the Bernoulli equation is then solved at each one of these points. A power series expansion is used to represent the horizontal and vertical components of the velocity at each of the grid points. Using Dias and Tuck's method, theoretical profiles of the upper and lower nappes were computed for weirs inclined at various angles.

**FINDINGS:** The results obtained from Dias and Tuck's method were compared to empirical results obtained from the U.S. Bureau of Reclamation (1948). The Bureau of Reclamation performed profile measurements on water flowing over vertical weirs and over weirs inclined at horizontal to vertical slopes of 1:3, 2:3, 1:1, 2:1, and 4:1. Results from Dias and Tuck's methods compared very well to the Bureau of Reclamation's measurements (fig. 2). However, at the lower angles (2:1 and 4:1 slopes) Dias and Tuck's method predicted slight ripples in the water surface upstream of the weir crest.

**INTERPRETATION:** The slight differences between the Bureau of Reclamation's profiles and Dias and Tuck's profiles at high angles can be explained by the different conditions under which the profiles were calculated. Dias and Tuck's method for calculating free-surface flows over an inclined weir is developed only for an infinitely deep approach channel. The Bureau of Reclamation's measurements, on the other hand, were, of course, performed in a channel of finite depth. The Bureau of Reclamation data with the smallest approach velocity head were used in the comparisons to the theoretical results. It is not known why ripples appear on the water surface profile at the lower angles. It is hoped that increasing the number of mesh points will reduce these ripples and smooth out the profile. However, increasing the number of mesh points dramatically increases the calculation time.

The good comparison between the theoretical results and empirical measurements indicates that theoretical results can be used to further the understanding of water flow over inclined weirs. By comparing the theoretical profiles at different angles, it is hoped that the accuracy of the empirical discharge equation developed last year can be improved.

**FUTURE PLANS:** Reasons for the calculated ripples on the water surface profile at low angles need to be investigated. Also, more numerical profiles need to be calculated for angles different from the ones tested by the Bureau of Reclamation. Once this is done, theoretical contraction coefficients can be obtained from the profiles. It is also planned to modify Dias and Tuck's method to calculate free surface profiles for inclined weirs in channels of finite depth.

**COOPERATORS:** UMA Engineering, Imperial Irrigation District, and Armtec, Inc.

**REFERENCES:**

Dias, F. and Tuck, E.O. 1991. "Weir Flows and Waterfalls." *J. Fluid Mech.*, Vol. 230, p. 525-539.

U.S. Bureau of Reclamation. 1948. *Studies of Crests for Overfall Dams*. Bulletin 3. Boulder Canyon Project, Final Report. U.S. Bureau of Reclamation, U.S. Department of Interior, Denver, CO. 186 pp.

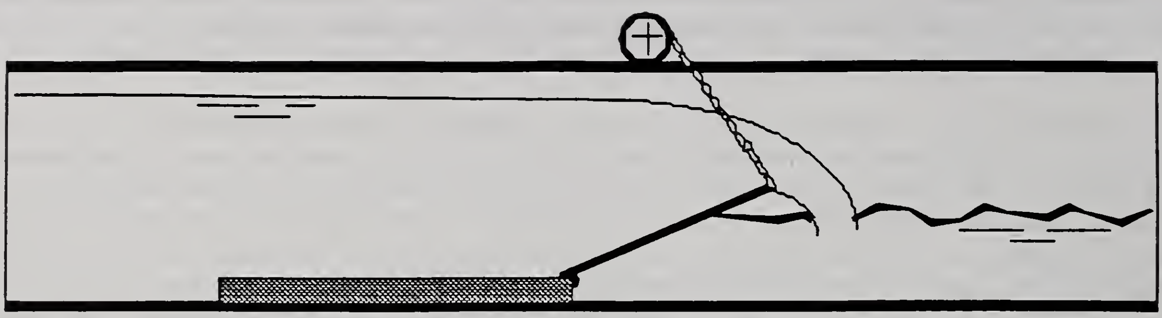

Figure 1. General schematic of an overshot gate.

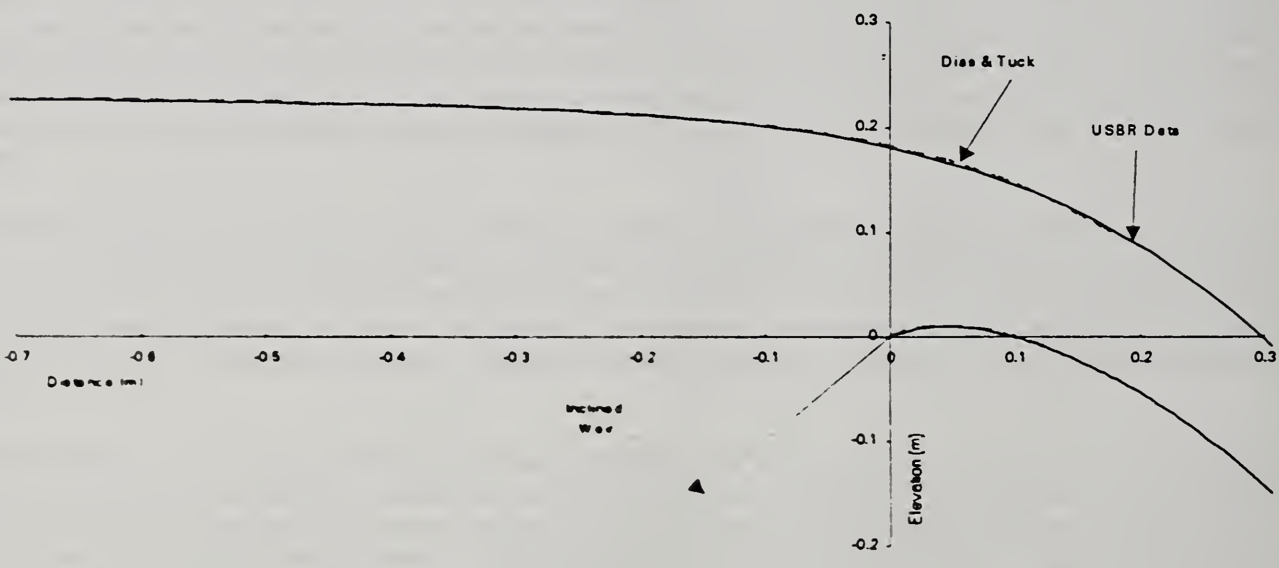


Figure 2. Comparison of USBR profile data with Dias and Tuck method for weir inclined at a 1:1 slope.

# IRRIGATION CANAL AUTOMATION

A.J. Clemmens, Supervisory Research Hydraulic Engineer; and
R.J. Strand, Engineering Technician

**PROBLEM:** Modern, high-efficiency irrigation systems require a sufficiently flexible and stable water supply . Open-channel water delivery distribution networks are typically not capable of this high level of service. Stable flows can be achieved when little flexibility in allowed since canal operators can force canals flows to be relatively steady. Allowing more flexibility increases the amount of unsteady flow and leads to more flow fluctuations.

Most canal systems operate with manual upstream control. A constant water level at each offtake is maintained to keep delivery flow rates constant. The disadvantage of this system is that all flow errors end up at the tail end of the system. In large canals, supervisory control systems are used to adjust volumes in intermediate pools to keep differences between inflow and outflow more evenly distributed in the system or simply stored until a balance is achieved. Smaller canals with insufficient storage need more precise downstream control methods than are currently available. Development of improved canal control methods requires convenient simulation of unsteady flow by computer. Many computer models of unsteady canal flow have been built in the last twenty years, some very complex and expensive, designed to model very complicated systems. Only recently have these programs been geared toward canal automation so that simulation of control algorithms could be efficiently made.

The objective of this research is to develop tools to promote the adoption of improved canal operating methods. This includes development and testing of canal control algorithms, development of necessary sensors and hardware, development of centralized and local control protocol, refinement of simulation models needed for testing these methods, and field testing of algorithms, hardware, and control protocol.

**APPROACH:** Control engineering will be used to develop control algorithms for one or more canals within the Maricopa-Stanfield Irrigation and Drainage District (MSIDD). These control algorithms will be written into control software for the central computer. Where possible, as much logic as practical will be written into the Remote Terminal Unit (RTU) software so that control can be more precise. New gate position sensors will be developed and tested to provide finer resolution of gate movement, while still providing absolute position. Several control algorithms will be tested to compare the various advantages and disadvantages of these controllers and tuning methods.

A Cooperative Research and Development Agreement between ARS and AUTOMATA, Inc., was established for the purpose of developing off-the-shelf hardware and software for canal automation. We will work closely with AUTOMATA in the application and testing of this new hardware and software.

**FINDINGS:** An ASCE task committee completed its preliminary work on classifying control algorithms, defining the influence of canal properties on canal controllability, and developing of test cases. These results provide a strong background for the current studies.

Field testing of simple canal control algorithms was performed on MSIDD's WM canal with the help of Jan Schuurmans, Delft University of Technology, The Netherlands, and his two students, Michael Ellerbeck and Guido Liem. Michael developed the linearized model of the WM canal from which Guido developed specific controllers with MATLAB. The control routines were imbedded into supervisory control software written by Ken Taylor at Central Arizona Irrigation and Drainage District. No gate position sensors were available on the WM canal, thus we relied entirely on communications (i.e., when we asked the gate to move x mm and we received verification, then it moved x mm). This proved to be unsatisfactory. Also, the method used by the district to control gate motors, while providing some safety, was not efficient enough for real-time automatic control.

Gate flow-rate control proved to be a more difficult problem than anticipated. It has been shown that control of flow rate gives better canal response than control of gate position. However, achieving accurate flow-rate control is not always easy. Only rudimentary flow-rate control was implemented during field testing.

Properly modeling canal conditions was essential. The conditions of the real canal were significantly different from the approximate canal, in terms of automatic control. In particular, it was found that the dynamic portion of pool 5 was actually extremely small, making it almost uncontrollable with pure feedback.

Figure 1 shows a comparison between the linearized model of canal response and the measured response. Here, the second and third gates were moved for a brief time and then moved back to their original position. Note that the results of these small changes persisted for a long time. Such tests were performed on all gates for the WM canal, with results similar to Figure 1.

Figure 2 shows a simplified version of new proposed controller. Here, the flow-rate control function at the gate is separated from both the feedback and feedforward components. Placing this portion within the RTU will allow flow-rate control to be made on a shorter time scale than feedforward and feedback (and with limited radio communication).

Figure 3 shows the results of one of the relatively successful feedback control field tests. This test was made on April 10, 1995. The gate downstream from pool 6, gate 6, was set to automatic flow-rate control. Gate 7 was closed, and the eighth pool was empty. A groundwater well pumping into pool 3 was shut off. Figure 3 shows the results of the controller in terms of deviation from water level targets (e.g., M-1 for pool 1) and gate positions (e.g., G-1 for gate downstream from pool 1, expressed as flow rate based on upstream water level being at the target level). A simple PI controller was used without anticipation and without a Smith Predictor (i.e., like ELFLO). Gates 1-3 opened very quickly as expected. Gate 3 was not able to maintain constant downstream flow, and thus the level at pool 4 changed. Pools 1 and 2 returned to set point quickly, while pools 3 and 4 did not. This had a negative effect on pools 5 and 6. Pools 3 and 4 not returning to set point resulted from high gate sensitivity.

If such a situation had occurred when operators were not on duty or were at another site, the levels downstream from pool 2 would all have fallen at least 20 cm. Even this simple controller had the levels back within 2 cm after an hour. While not very satisfactory from a theoretical perspective, for the existing gate hydraulics, this level of control would be operationally acceptable. These results were reasonable considering the physical hardware available and the low level of controller sophistication.

Through a cooperative agreement, Cal Poly adapted the CANALCAD program to fit more fully the needs of canal automation testing at MSIDD. It now more easily handles centralized control algorithms.

INTERPRETATION: The results of initial field testing were encouraging. Gate sensitivities caused more difficulties than anticipated, emphasizing the need for accurate feedback on gate position and movement. Preliminary results on this canal point to the need to also include known, scheduled changes within the control system. These changes can easily be handled with feedforward, with minor adjustments or correction made with feedback. However, this means interfacing the control system with the water ordering system. The feedback algorithms also need additional testing.

FUTURE PLANS: The MSIDD WM canal will be outfitted with new RTUs that are more easily programmed with the necessary automation control functions. New gate position sensors will also be installed. Once these are in place, the automation logic will be programmed into the RTUs and central computer software. Field testing of the new routines and sensors will be made off-line. Then, new controllers for the canal will be designed and field tested.

A lateral canal with properties somewhat different from the WM canal will be selected for future analysis and testing of control algorithms. Discussions have also begun with the Salt River Project regarding development and testing of Automation on the Arizona canal.

COOPERATORS: Lenny Feuer, Automata, Inc.; Gary Sloan, MSIDD; Ken Taylor, CAIDD; Jan Schuurmans, Delft U. of Technology, The Netherlands; Charles Burt, Cal Poly; Bob Gooch, Salt River Project; Victor Ruiz, IMTA; Pierre Olivier Malaterre, CEMAGREF, Montpellier, France

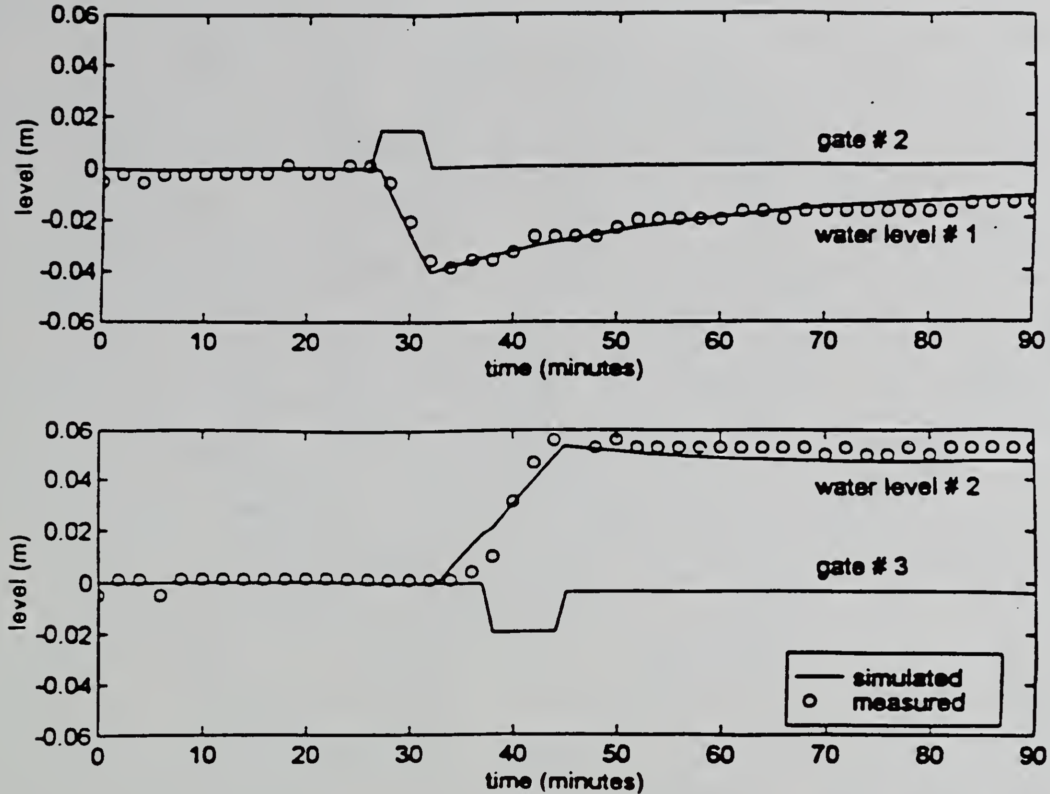


Figure 1. Measured and predicted open loop response of water levels to short-duration changes in gate position for first two pools of MSIDDs WM lateral canal, March 29, 1995.

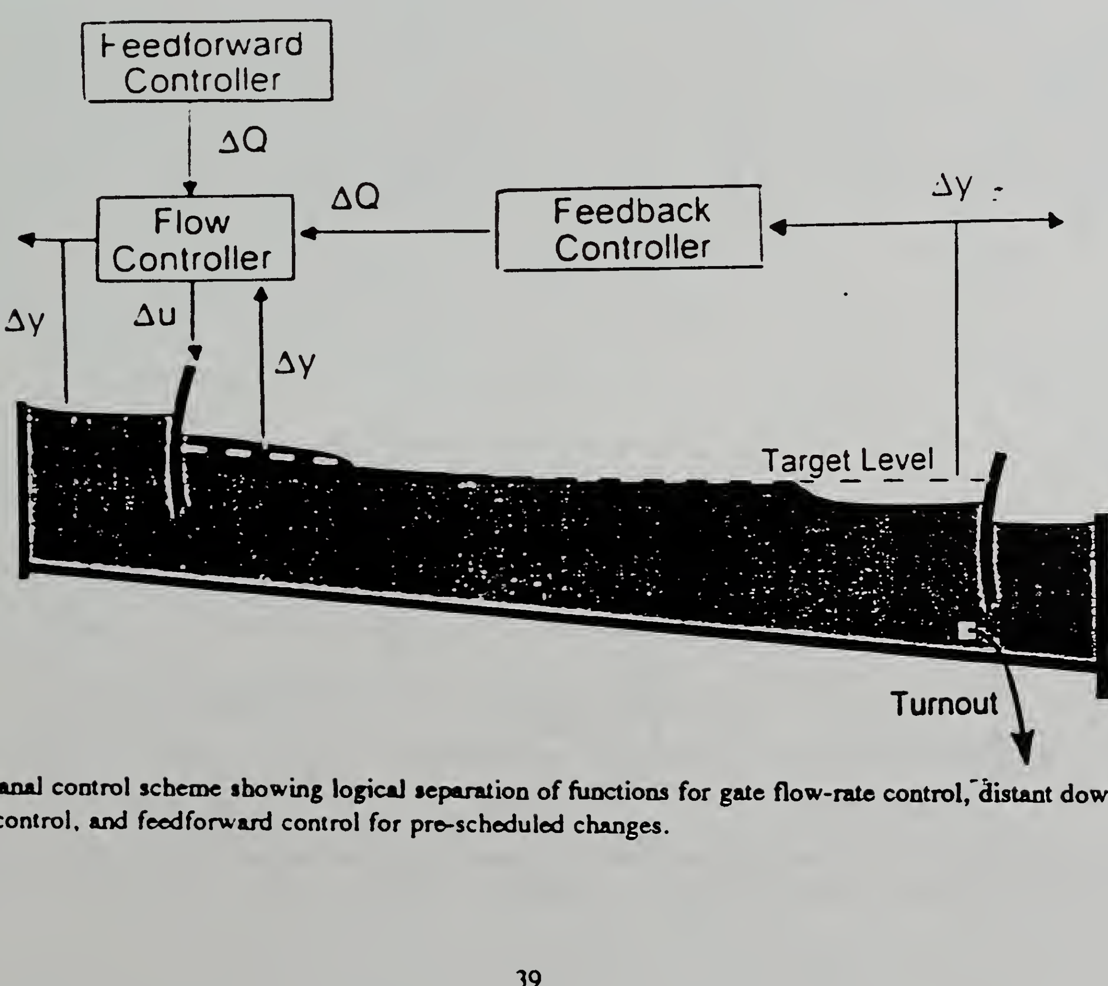


Figure 2. Canal control scheme showing logical separation of functions for gate flow-rate control, distant downstream water-level control, and feedforward control for pre-scheduled changes.

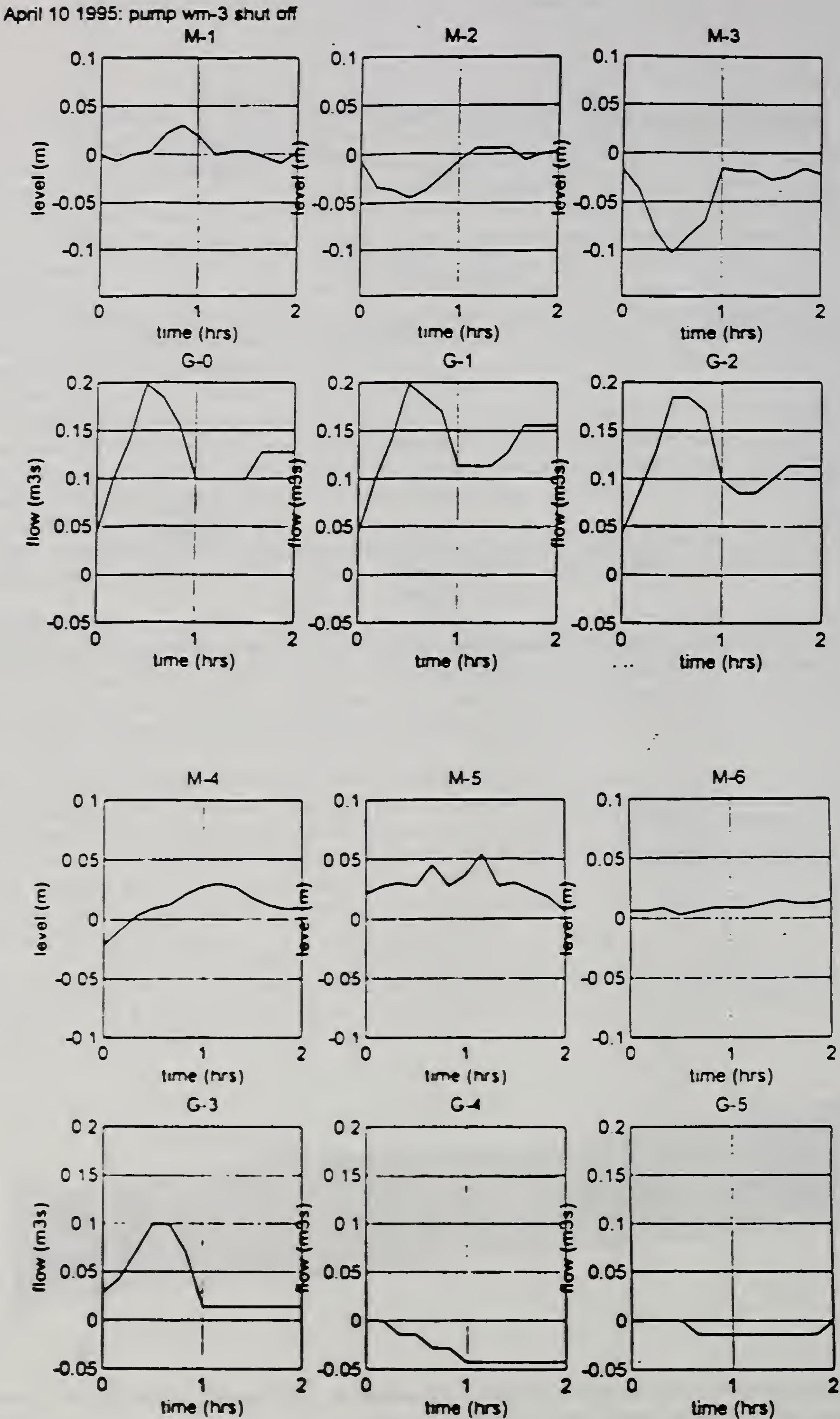


Figure 3. Measured water levels and calculated flow rates (based on assumed constant upstream level) for the first six pools of MSIDDs WM lateral canal for feedback control test of simple PI controller, April 10, 1995.

# PROTECTION OF GROUNDWATER QUALITY

# WATER REUSE AND GROUNDWATER

H. Bouwer, Research Hydraulic Engineer

**PROBLEM:** Increasing populations and finite water resources demand water reuse, as do increasingly stringent treatment requirements for discharge of sewage effluent into surface water. The aim of this research is to develop technology for optimum water reuse and the role that soil-aquifer treatment can play in the potable and nonpotable use of sewage effluent. In Third World countries, simple, low-tech methods must be used. Such methods will be applied to demonstration projects in the Middle East and North Africa under the White House Middle East Peace Initiative and the Technology for International Environmental Solutions (TIES) program of USDA and EPA.

**APPROACH:** Technology based on previous research at the USWCL and more recent research are applied to new and existing groundwater recharge and water reuse projects here and abroad. Main purposes of the projects range from protecting water quality and aquatic life in surface water to reuse of sewage effluent for nonpotable (mostly urban and agricultural irrigation) and potable purposes.

Cooperative research has been continued with The University of Arizona to manage clogging layers for optimum benefits in infiltration systems for groundwater recharge and soil-aquifer treatment where clogging layers are not wanted, and in constructed wetlands, aquaculture ponds, and animal waste lagoons where clogging layers are wanted. Both hydraulic and water quality aspects are considered. New research is being developed on novel approaches, such as seepage trenches and techniques for well or trench recharge with sewage effluent without reverse osmosis or other membrane filtration as pretreatment.

**FINDINGS:** Field and laboratory tests continue to show the usefulness of recharge and soil-aquifer treatment in water reuse. Main issues still are sustainability of soil-aquifer treatment and fate of recalcitrant organic compounds. Tests with experimental recharge trenches indicate acceptable recharge rates if suspended solids are effectively removed.

**INTERPRETATION:** Results will be applied to existing and planned groundwater recharge and soil-aquifer treatment systems. Research proposals for funding by research foundations have been prepared. Various national and international conferences on groundwater recharge, soil aquifer treatment, and water reuse were participated in. Other national and international conferences are being planned and prepared.

**FUTURE PLANS:** Future plans primarily consist of initiating and coordinating research on groundwater recharge and water reuse issues by other institutions and responding to requests to write, speak, and advise.

**COOPERATORS**: The University of Arizona.

# PHYSICAL, CHEMICAL, AND BIOLOGICAL CHARACTERISTICS OF A SCHMUTZDECKE: EFFECTS OF SEEPAGE AND WATER TREATMENT IN WASTEWATER DISPOSAL FACILITIES

Herman Bouwer, Research Hydraulic Engineer; and Martha Conklin, Professor of Hydrology

**PROBLEM:** Soil clogging occurs during artificial recharge and effluent disposal operations. Reduced infiltration and consequent ponding are largely attributed to development of a slime layer, or "schmutzdecke." The objectives of this project are to determine: (1) physical, chemical, and biological processes occurring in the schmutzdecke, (2) improvement of water quality after it has moved through the schmutzdecke (for example, effect of schmutzdecke on pathogen removal or nitrogen speciation), (e) how schmutzdecke should be managed for specific needs (in particular, to evaluate how schmutzdecke affects flow of essential nutrients: nitrogen and phosphorous), and (4) how hydraulics affect schmutzdecke.

**APPROACH:** During the third year of this project, fifteen soil columns (3.25" i.d. x 39" length) were used to study surface clogging layers. An additional column (3.25" i.d. x 78" length) has been constructed. Columns are packed with poorly-sorted Agua Fria sand, Sweetwater sandy loam, or North Pond silty sand. Filtered primary, dechlorinated secondary, ozonated secondary, and denitrified effluents were applied to columns in alternating wet/dry cycles. Various blends of secondary and primary effluent were applied during denitrification studies. Samples were collected from column influent and effluent for measurement of dissolved organic carbon (DOC), UV absorbance at 254 mm (UV-254), trihalomethane formation potential (THMFP), pathogens, and nitrogen species. Ozonation of secondary effluent was performed at a transfer ratio of 1:1 and 0.5:1 (ozone to organic carbon). Biodegradable dissolved organic carbon (BDOC) tests were used to determine the fraction of DOC potentially degradable by aerobic bacteria over a five day period. A control column for each soil type received sodium azide-amended effluent for distinguishing aerobic versus nonaerobic removals of organics, nitrogen, and pathogens through schmutzdecke.

## FINDINGS AND INTERPRETATION:

**Removal of Organics**—Table 1 lists organic removal efficiencies for 18-cm and 1-m columns containing Sweetwater sandy loam. Differences in through-column removal of DOC were significant for 1-m columns containing sandy loam (56%) and sand (48%). Removal for silty sand was 44%. Mean column effluent concentrations of DOC were 5.1, 5.5, and 6.2 mg/L for sand, sandy loam, and silty sand, respectively. Removal of UV-absorbing organics was not significantly different for columns containing sand and sandy loam (22 and 20%, respectively). Column effluent UV-254 absorbances were 0.101, and 0.108/cm for sand and sandy loam, respectively. Column effluent UV-254 was significantly higher (0.133 /cm) for the silty sand, from which desorbable organics were leached throughout a 6-month period of effluent percolation. Comparison of through-column organic removals for biologically active and inhibited columns indicated that aerobic biological processes play a dominant role in removal of both DOC and UV-254. Removals of DOC across columns receiving azide-amended effluents were on the order of 5%. For the inhibited columns, differences in levels of organic removal attributable to soil type were not evident.

**Nitrogen Transformations**—Ammonia breakthrough was observed primarily in the sand columns fed with secondary effluent after two to three days of flooding While typically less than 5% of influent nitrogen was in the nitrate form, nitrate was flushed out of the columns at extremely high concentrations over the first few hours of a wet period before dropping to near influent concentrations after one day of operation. The "nitrate flush" was attributed to nitrification of ammonia during the drying period and its subsequent release as nitrate in the wetting period. Nitrogen removal was negligible in columns fed solely with secondary effluent. A 50/50 blend of primary and nitrified secondary effluents applied to a 1 meter soil column yielded 72% removal of nitrogen based on mass balances of inorganic aqueous nitrogen species. The lowered ammonia content of blended effluent also contributed to a reduced initial flush of nitrate during flooding periods. A management strategy employing nitrified/non-nitrified effluent blends would provide a degree of control over nitrogen transformations and enhance nitrogen removals during SAT.

**Removal of Pathogens**—Average through-column bacteriophage removals in secondary effluent were 93 and 76% for sandy loam and sand, respectively, a difference which was significant at $p = 0.001$. Average bacteriophage removal in azide-inhibited sand columns was 45% suggesting that aerobic soil biota may contribute towards virus removal. Removal of poliovirus through sand was equal or greater than removal of indigenous bacteriophage, indicating the suitability of

bacteriophage as a conservative indicator for poliovirus removal. Through-column removal of *Cryptosporidium* oocysts was 3.8 and 3.9 logs through 1-m of sandy loam and sand, respectively.

**Comparison of Primary versus Secondary Effluents**--Once columns fed filtered primary effluent reached steady-state performance, percent removals of DOC and UV-254 were greater than percent reductions achieved for secondary effluent (table 1), however, the final water quality for secondary versus primary effluent ($5.5 \pm 1.4$ mg/l vs $4.7 \pm 1.5$ mg/l and $0.108 \pm 0.006$ $cm^{-1}$ vs. $0.100 \pm 0.011$ $cm^{-1}$ for DOC and UV-254, respectively) was comparable. Enterovirus removals were worse for primary effluent (85%) than observed for secondary effluent. Significant log removals of total coliforms (3-4 log units) and fecal coliforms (5-7) were achieved, with fecal coliforms often below detection limits (1 MPN/100 ml) in the column effluent. There was very little phosphorus removal observed for the primary effluent.

**Compressibility Studies**--Work has continued on one-dimensional consolidation testing on statically recompacted soil specimens, specimens with mixed cultures of algae, and clogging layer samples form UA and ASU soil columns. A parametric study was conducted to assess the range of expected effective stresses on clogging layers due to infiltrating water. This lead to adoption of a two layered conceptual model of the clogging layer: an upper layer consisting of particulate matter subject to compression under seepage forces and a lower layer consisting of native soil with entrained particulate matter, and hence, reduced conductivity. A computer spreadsheet model has been developed which simulates growth, death, and sedimentation of algae and other particulate matter in the infiltration basin.

**FUTURE PLANS:** Future studies will include an examination of the fate of specific classes of organic compounds (e.g., humic acids, fulvic acids, hydrophilics, and chloraectic acids) through schmutzdecke. A two-meter column containing Agua Fria sand is now in operation; experiments are in progress to determine through-column removal efficiencies for DOC, UV-254, THMFP, nitrogen species, indigenous bacteriophage, and seeded *Cryptosporidium* oocysts. Additional experiments are underway to establish the effect of applied light on schmutzdecke, and soil oxygen levels on organic removal efficiency.

Compressibility studies which will be completed include: consolidation testing of statically compacted soil specimens, sedimented soil specimens, various algae types, and other clogging layer components as required; consolidation tests on samples of various clogging layers, which were produced in infiltration columns or taken from an operating SAT site; and experiments regarding the effect of variation in pond depth on the infiltration rate. Data obtained will be used to improve and parameterize models of infiltration basins and flow through clogging layers.

**COOPERATORS:** Martha Conklin, Assistant Professor; L.G. Wilson, Hydrologist; Robert Arnold, Associate Professor; C.P. Gerba, Professor; Kevin Lansey, Assistant Professor; David Quanrud, Peter Chipello, Pedro So-Navarro, John Hillman, Katanya Miles, Sean Carroll, and Mary Quinonez, Research Assistants, University of Arizona; and Sandra Houston, Associate Professor; Peter Fox, Assistant Professor; and Peter Duryea, Research Associate, Arizona State University.

Table 1. Comparison of through-column percent removal of DOC and UV-254 as a funciton of soil depth and soil type.

| | Soil Depth | | | | | |
|---|---|---|---|---|---|---|
| | 18 cm | | 1 m[1] | | 1 m[2] | |
| Effluent Type | % DOC removed | %UV-254 removed | %DOC removed | %UV-254 removed | %DOC removed | %UV-254 removed |
| Secondary | 23.2 | 12.3 | 56.0 | 20.4 | 48.0 | 22.1 |
| | ±5.3 | ±6.4 | ±10.4 | ±5.7 | ±7.3 | ±5.7 |
| Ozonated | 22.1 | 9.9 | n/a | n/a | 59.7 | 23.0 |
| Secondary | ±5.7 | ±4.1 | | | ±7.3 | ±5.5 |
| Inhibited | 6.4 | 0.9 | 9.8 | -4.7 | 14.6 | 5.7 |
| Control | ±3.9 | ±2.8 | ±9.5 | ±6.2 | ±11.1 | ±12.0 |
| Filtered | - | - | 84.2 | 65.5 | - | - |
| Primary | | | ±26.7 | ±9.5 | | |

[1]Sweetwater sandy loam
[2]Agua Fria sand

## NITROGEN FERTILIZER AND WATER TRANSPORT UNDER 100% IRRIGATION EFFICIENCY

R.C. Rice, Agricultural Engineer; F.J. Adamsen, Soil Scientist;
and D.J. Hunsaker, Agricultural Engineer

**PROBLEM:** The rising trend in nitrate levels of groundwater suggests that nitrogen fertilizers are frequently being transported beyond the root zone. Improving management practices in irrigated agriculture may lead to better control of nitrogen contamination of the groundwater. Using feedback techniques such as soil and crop nitrogen status and more frequent fertilizer applications with smaller application rates are suggested as better management practices. Previous studies indicated that 100% irrigation efficiency during the growing season limited the transport of nitrogen to the vadose zone. However, preferential flow and spatial variability may cause water and nutrient losses from the root zone even under ideal management conditions. The objective of this study is to determine the movement of water and nitrogen fertilizer in the soil profile when irrigating at 100% irrigation efficiency and to develop associated Best Management Practices (BMPs) to protect the quality of underlying groundwater.

**APPROACH:** Studies on cotton grown using level basin flood irrigation were continued in 1995. The experimental design was a complete randomized block with six fertilizer-water application treatments and three replications. Each experimental plot was 108 $m^2$. Micro-plots were established in each plot and fertilized with nitrogen-15 labeled fertilizer. Potassium bromide was applied as a tracer with the first fertilizer application. Water movement in the soil profile was characterized with soil water content and tracer analysis. Evapotranspiration was estimated from soil water depletion data and energy balance techniques using meteorological data collected at the site. Irrigation scheduling was determined using a soil water balance method. Experimental treatments were as follows: 1) irrigation and fertilizer applications were made according to current farm practices, with a) 100% irrigation efficiency, b) 80% irrigation efficiency, and c) 20% deficit irrigation; 2) irrigation applied fertilizer applications were scheduled according to residual soil, petiole $NO_3$-N feedback with a) 100% irrigation efficiency, b) with 80% irrigation efficiency, and c) with 20% deficit irrigation.

**FINDINGS:** Analysis of the soil samples have not been concluded. Preliminary analysis of the data indicate similar results as in previous years as shown in figure 1. The nitrate concentrations were greatest near the surface and decreased to low values at 60 to 90 cm. A nitrate peak occurred at depths of 150 to 180 cm. The source of the nitrate peak was residual nitrogen in the profile that was leached by early irrigations. As in previous years, less nitrate was leached below 100 cm at 100% irrigation efficiency and deficit irrigation for both the standard and BMP treatments. The deficit irrigation treatment had the least $NO_3$-N below the root zone. The BMP treatments showed lower levels of nitrate in the deficit irrigation and 100 % efficiency treatments. At 80 % efficiency, however, the BMP treatment was similar to the standard treatment.

**INTERPRETATION:** Management practices such as applying fertilizer at more frequent intervals and irrigating at 100% efficiency during the growing season may result in less leaching of the nitrate below the root zone. Nitrate levels increase during the fallow period probably from mineralization of organic nitrogen. Existing nitrate in the soil profile at the start of the growing season may be leached when nitrate is moved below the effective root zone from early irrigations before the crop is established. Best management practices need to consider preplant soil nitrogen status, timing of fertilizer and irrigation applications and build-up of nitrate during the noncrop season.

**FUTURE PLANS:** Nitrate leaching under different irrigation methods (drip or sprinkler) will be investigated. Fertilizer application methods such as chemigation (applying with irrigation water), broadcast, side dressing, and foliar spray will be investigated.

**COOPERATORS:** J.E. Watson, University of Arizona, Maricopa Agricultural Center

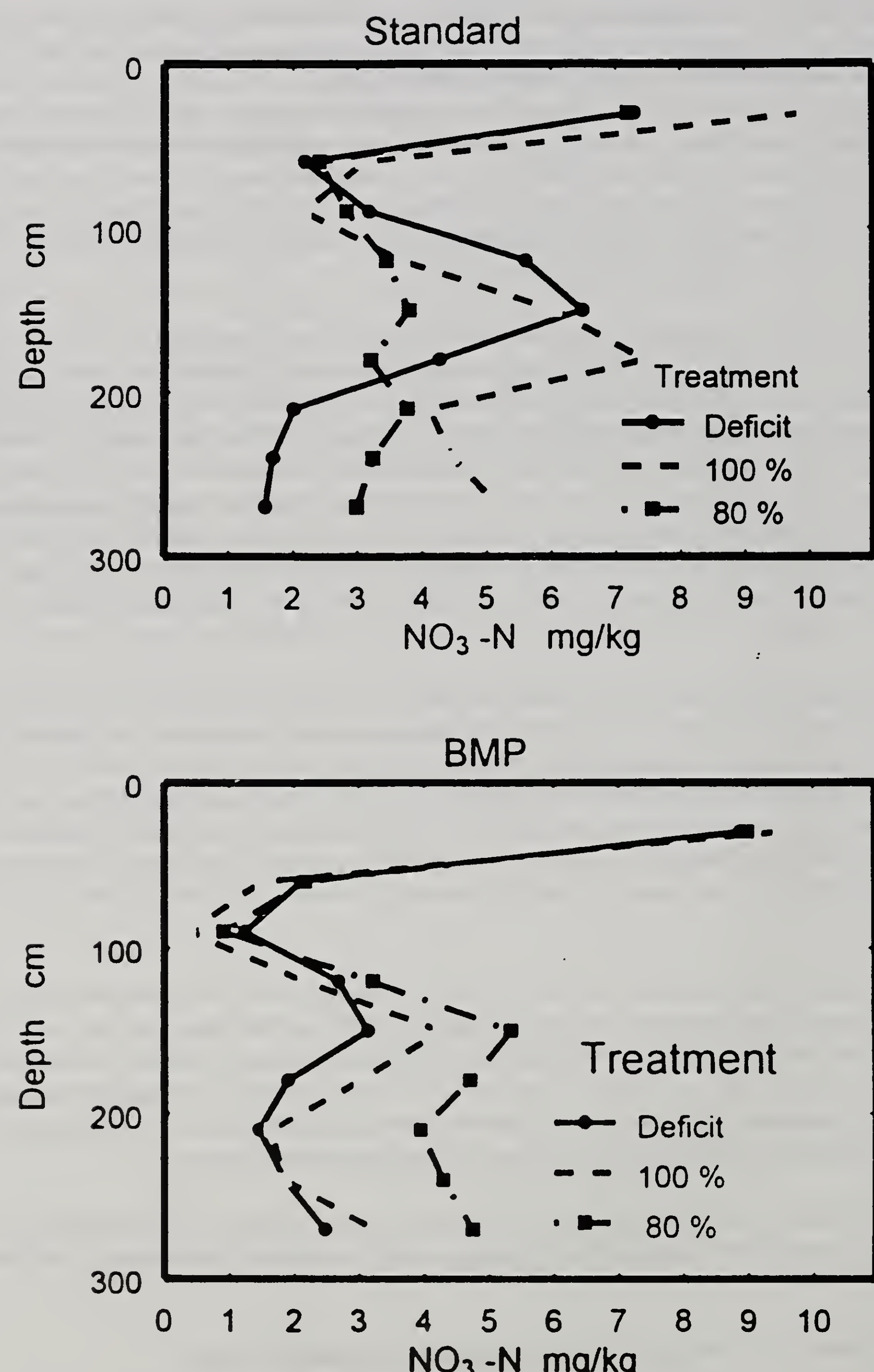


Figure 1. Nitrate - N with depth for standard and BMP treatments at 10% irrigation efficiency, 80% irrigation efficiency, and 20% deficit irrigation.

# NITROGEN BUDGETS OF IRRIGATED CROPS USING NITROGEN-15 UNDER HIGH EFFICIENCY IRRIGATION

F. J. Adamsen, Soil Scientist; R. C. Rice, Agricultural Engineer; F. S. Nakayama, Research Chemist; D. J. Hunsaker, Agricultural Engineer; and H. Bouwer, Research Hydraulic Engineer

**PROBLEM:** Nitrate is the pollutant most commonly found in groundwater. The contribution of nitrate to groundwater pollution carried by deep percolating irrigation water could be reduced or eliminated by the development of existing and new technologies. This requires a better understanding of the total nitrogen required by the crops produced and the timing of nitrogen uptake as well as chemical and water transport in the soil environment. Careful timing of fertilizer applications and prudent operation of irrigation systems to reduce the amount of water lost below the rooting zone can reduce the movement of water and chemicals to groundwater. Theoretically, irrigating at 100% efficiency and carefully controlling fertilizer amounts and timing of applications should lead to no deep percolation and no fertilizer leaching losses. Crop leaching requirements could be met when soil nitrate levels are lowest. However, because of spatial variability, preferential flow, and incomplete uptake of nitrogen by the crop, 100% irrigation efficiency and optimum nitrogen management may still produce some deep percolation and transport of nitrate to groundwater.

**APPROACH:** Research is being conducted through a series of experiments to evaluate water and nitrogen management practices. Wheat was grown in the 1991-1992, 1992-1993 and 1993-1994 seasons using level-basin flood irrigation. Cotton was planted in 1993, 1994, and 1995. Future experiments will use other irrigation methods such as drip and sprinkler irrigation. The experimental design is a complete randomized block with six fertilizer-water application treatments and three replications. Experimental plots were approximately 81 $m^2$ in size in 1991 and 108 $m^2$ in 1992, 1993, 1994 and 1995. A different conservative tracer was applied with each irrigation, and nitrogen-15 tagged fertilizer was applied to three micro-plots in each main plot in 1991 and two micro-plots in 1992, 1993 and 1994. The benzoic acid tracers used in previous years caused problems with cotton growth resulting in deformed plants and reduced yield, so the cotton received only bromide as a conservative tracer at the beginning of the 1995 growing season. Micro-plots were approximately 1 $m^2$ in 1991 and 1992 and 1.5 $m^2$ in 1993 and 1994. This allows a complete water and nitrogen balance, including the amount of nitrogen removed with the harvested crop, percolation losses and volatile losses by difference. The nitrogen status of the crop was determined by tissue analyses and leaf chlorophyll content with a chlorophyll meter. Chlorophyll measurements may allow a rapid cost-effective method for determining the nitrogen status of a crop in real time and may be useful in determining the amount and timing of fertilizer nitrogen. Water movement in the soil profile is characterized by soil water content and tracer analysis. Evapotranspiration is estimated from energy balance techniques.

Experimental treatments include 1) a "standard" fertilizer and irrigation management procedure where irrigation and fertilizer applications are scheduled according to current farm practice with irrigation amount as 100% of estimated evapotranspiration (ET), 2) same as treatment 1 except with 120% of ET, 3) same as treatment 1 except with a deficit irrigation equivalent to 80% ET, 4) irrigation-water-applied fertilizer application (chemigation) scheduled according to residual soil, petiole $NO_3$-N feedback, and leaf chlorophyll content with irrigation amount as 100% of ET, 5) same as treatment 4 except with 120% of ET, and 6) same as treatment 4 except with a deficit irrigation equivalent to 80% ET.

**FINDINGS:** Yields of lint and seeds were slightly higher in the BMP treatments for the 80% and 100% ET irrigation treatments, but the reverse was true for the 120% ET irrigation treatment by a much greater amount (Tables 1 and 2). Lint and seed yields increased with increasing irrigation for the Standard fertilizer treatment; but for the BMP fertilizer treatment the yields, increased from 80% to 100% ET irrigation treatments but decreased slightly from the 100% to 120% ET treatment. The 1995 cotton experiment was planted in a different field than was used in 1993 and 1994. The new field has some sandy areas, and this may have affected the yields in some plots. Mechanical analyses are being performed on all of the plots, and the results will be used to determine if soil texture may have affected some treatments more than others or whether some variable in the treatment affected the yields at the highest water application rate.

In 1995, lint yield of cotton was as much as 3.5 times greater than for the same treatment in 1994. This was due to the use of fluorinated benzoic acid tracers used in 1994. Seed yields of cotton responded similarly.

Renovation of the laboratory facilities at USWCL has delayed the analysis of many of the soil samples for inorganic nitrogen and nitrogen-15. These analyses will be completed as soon as is practical.

INTERPRETATION: The use of BMP nitrogen management resulted in yields of lint and seed that were as high as those from the standard treatment for two of the levels of water application (Tables 1 and 2). The BMP nitrogen management system used approximately 10% less nitrogen than did the Standard treatment, which means lower percentage of residual nitrogen in the soil. This means far less nitrogen available for leaching in the BMP management system.

There is no obvious reason for the trend of BMP fertilizer treatments yielding higher than the Standard fertilizer treatment in the 120% ET water treatment. There may have been some differences in soil water holding capacity amongst plots that affected some treatments more than others.

Yields of cotton were still highest at the 120% ET irrigation level (Table 1). Either the estimates used for ET or the loss of water below the root zone is greater than expected. Cotton is sensitive to moisture stress and errors in water use, or water loss can result in unexpected water stress on the plant. Additionally, variations in soil properties away from points where water use measurements are made can result in portions of the field receiving water after stress has affected some of the plants in the field. Further analysis of all of the data that has been collected during this study should answer these questions.

FUTURE PLANS: Analysis of the data from the current and past years studies will be completed and recommendations for improvements in the current BMPs for water and nitrogen will be developed. Data from past years indicate that mineralization of nitrogen during fallow periods results in nitrate being leached below the root zone when the preplant irrigation is applied. To overcome this problem, new BMPs will look at the entire cropping system rather than the crop-specific recommendations currently used. Additional irrigation methods also need to be investigated. The rates of movement of chemical tracers and labeled nitrogen will be used to assess the impact of preferential flow on the movement of nitrate and other pollutants to groundwater. The data set should be suitable for evaluating current soil models that predict the quality of water moving below the root zone. If no suitable models exist, a model development and verification effort can be initiated.

COOPERATORS: J. E. Watson, The University of Arizona Maricopa Agricultural Center; T. L. Thompson, The University of Arizona Department of Soil and Water Science.

Table 1. Lint yield of cotton from the 1995 irrigation and fertilizer management study.

| Nitrogen Application Method | 80% ET | 100% ET | 120 % ET | Average |
|---|---|---|---|---|
| | kg ha$^{-1}$ | | | |
| Standard | 767 | 1133 | 1317 | 1072 |
| BMP | 803 | 1170 | 1140 | 1038 |
| Average | 785 | 1151 | 1129 | 1022 |

Table 2. Seed yield of cotton from the 1995 irrigation and fertilizer management study.

| Nitrogen Application Method | 80% ET | 100% ET | 120 % ET | Average |
|---|---|---|---|---|
| | kg ha$^{-1}$ | | | |
| Standard | 1303 | 1820 | 2227 | 1,783 |
| BMP | 1323 | 1927 | 1853 | 1,701 |
| Average | 1,313 | 1,874 | 2,040 | 1,742 |

## EVALUATION OF RAPE AND CRAMBE AS POTENTIAL WINTER CROPS TO REDUCE NITRATE ACCUMULATION IN THE SOIL

F. J. Adamsen, Soil Scientist; W. L. Alexander, Agronomist; and R. C. Rice, Agricultural Engineer

**PROBLEM:** Formation of nitrate during fallow periods in irrigated cotton rotation systems can lead to leaching of nitrate to groundwater when preplant irrigations are applied in order to make the soil suitable for tillage operations. One solution to this problem is growing a winter crop that utilizes residual nitrogen and nitrate mineralized during the winter. Because of the cost of water, any crop grown in the winter under irrigated conditions must have an economic return in order to gain producer acceptance, and a crop must be found that can be planted after cotton is harvested in the fall and harvested before cotton is planted in the spring. Two crops that may meet these restrictions are rape and crambe. Industrial rape and crambe both contain erucic acid, which has industrial potential, and Canola types of rape are valuable as a source of unsaturated cooking oil. Both of these crops are short, cool season crops that may meet the short growing season requirement and have a significant nitrogen requirement that would take advantage of residual nitrogen in the soil.

**APPROACH:** Research is being conducted through a series of field experiments to evaluate yield potential and maturity dates of rape and crambe. One variety of crambe, one variety of mustard, one variety of spring-type industrial rape, and seven varieties of spring Canola type of rape were planted in the 1994-1995 growing season in 2 X 12.2-m plots on three planting dates from late October to early December. Row spacing was 0.25 m. For the 1995-1996 growing season, one variety of spring industrial rape, one variety of crambe, and ten varieties of spring Canola type rape will be planted with three planting dates from late October through mid-December. The spring industrial and two of the spring Canola types of rape are campestra types of the species *Brasica rapa*, while the other Canola types of rape are from the species *Brasica napus*.

**FINDINGS:** In the 1994-1995 crop year, rodent damage to the Canola types of rape was minimized through an aggressive rodent control program. Harvest dates varied from Apr 10 to May 5 (Table 1), which was later than in 1994. The later harvest dates in 1995 were a result of cool weather in the late spring. For the first planting date, as in 1994, R-500 was the earliest maturing along with Crambe and Hirta. The Canola types were all harvested within a four-day period from the first planting date. Crambe was the first to mature from the second planting date. The Hirta, R-500, and the Canola types were harvested on either Apr 27 or May 1. The third planting date was harvested from May 2 through May 5. A severe windstorm caused many of the varieties to shatter. The highest yields were achieved with A112 and Oscar at over 3500 kg ha$^{-1}$ (table 1 and fig. 1). In general, yields from the third planting date were lower than those from the first two planting dates. Part of the yield reductions were due to shattering at the end of the season. The yields of the mustard, Hirta, was only 1000 kg ha$^{-1}$.

**INTERPRETATION:** Yields of the mustard, Hirta, were lower than needed for economic viability for the crop. The plant grew well, matured early, and shattering was not a problem. Many weeds are closely related to mustard and present problems for control Based on the 1994-1995 results, Hirta will be dropped from the study. Crambe yields were over 2000 kg ha$^{-1}$ for the first two planting dates Yield of crambe in the third planting date was reduced by shattering losses associated with a windstorm in early May. The earliest harvest date was 12 days later in 1995 than in 1994 as a result of cool temperatures. The delay in harvest date also would delay planting of cotton. The cool temperatures delayed emergence and the development of cotton seedlings to such an extent that a delay in planting would not have affected cotton. Yields of Canola above 2500 kg ha$^{-1}$ are considered economical in the southeastern U. S. We were well above that for several varieties, indicating that Canola production in rotation with cotton is potentially economically viable in the desert southwest as a winter crop.

**FUTURE PLANS:** In 1996, evaluation of rape and crambe will be continued, additional early maturing varieties of rape from the Colorado breeding program will be added to the program, and earlier maturing varieties of Crambe will be sought. Irrigation and other agronomic studies will be conducted to make the yields of winter crops economical. Additional studies will be initiated to determine the water and fertilizer requirements of rape and crambe under local conditions. The results of the planting date by variety trial and water use and fertility trials will be used to develop a rotation system with cotton that will provide year-round cover on the soils which should improve year round nitrogen management.

**COOPERATORS:** Paul Raymer, Coastal Plain Experiment Station, Georgia; Larry Sernek, Agrigenetics, Madison,Wisconsin; Jennifer Mitchell Fetch, University of North Dakota, Fargo, North Dakota; Duane Johnson,, Colorado State University, Fort Collins, Colorado.

Table 1. Rape and Crambe yields in the 1993-1994 crop year at Maricopa Agricultural Center. All data is based on replication.

| Variety | Planting Date | Harvest Date | Yield kg $ha^{-1}$ | Planting Date | Harvest Date | Yield kg $ha^{-1}$ | Planting Date | Harvest Date | Yield kg $ha^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|
| R-500 | 28 Oct | 10 Apr | 2477 | 21 Nov | 1 May | 2198 | 15 Dec | 5 May | 1743 |
| Crambe | 28 Oct | 10 Apr | 1832 | 21 Nov | 23 Apr | 2971 | 15 Dec | 5 May | 2744 |
| Hirta | 28 Oct | 10 Apr | 839 | 21 Nov | 1 May | 1034 | 15 Dec | 5 May | 1032 |
| Cyclone | 28 Oct | 24 Apr | 1667 | 21 Nov | 1 May | 2775 | 15 Dec | 5 May | 2199 |
| A112 | 28 Oct | 24 Apr | 3804 | 21 Nov | 27 Apr | 3867 | 15 Dec | 2 May | 2391 |
| Bingo | 28 Oct | 23 Apr | 2552 | 21 Nov | 27 Apr | 3125 | 15 Dec | 2 May | 2306 |
| Oscar | 28 Oct | 23 Apr | 3721 | 21 Nov | 27 Apr | 3276 | 15 Dec | 5 May | 2674 |
| Iris | 28 Oct | 26 Apr | 2298 | 21 Nov | 27 Apr | 1985 | 15 Dec | 5 May | 2025 |
| 188-20-B | 28 Oct | 24 Apr | 1544 | 21 Nov | 1 May | 1424 | 15 Dec | 2 May | 1639 |
| 188-4-C | 28 Oct | 24 Apr | 2695 | 21 Nov | 27 Apr | 2428 | 15 Dec | 2 May | 1566 |

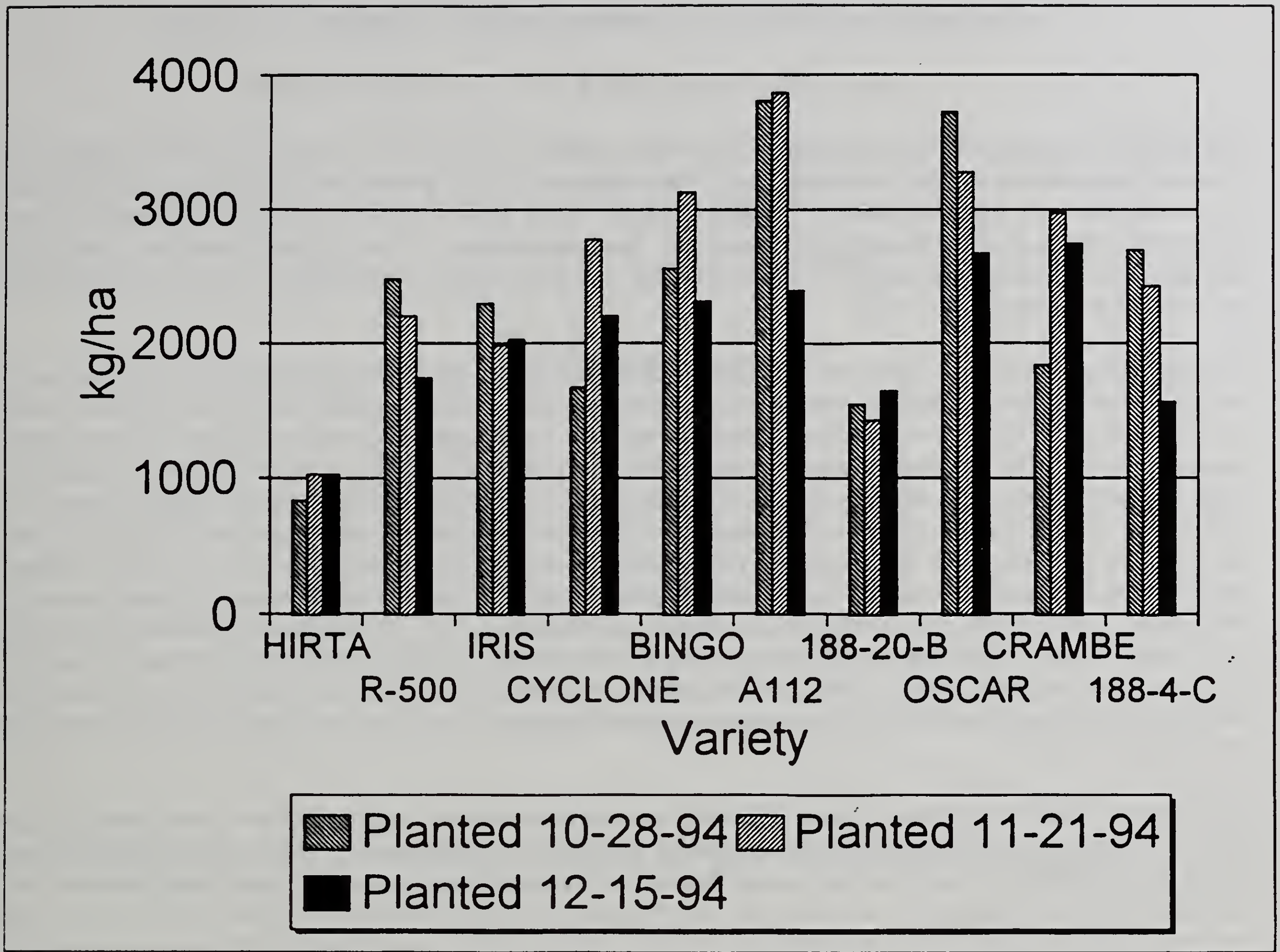


Figure 1 Yield of 1994 rape, crambe and mustard from three planting dates in the fall of 1994.

## ASSESSMENT OF NITRATE LEACHING UNDER COMMERCIAL FIELDS

F. J. Adamsen, Soil Scientist; and R. C. Rice, Agricultural Engineer

**PROBLEM:** Application of excess nitrogen to crops such as cotton and subsequent application of excess irrigation water can result in movement of nitrate to groundwater. When nitrate is found in groundwater, agriculture is usually assumed to be the source of the contamination. A number of surveys of Midwestern fields indicate that farm practices are responsible for at least part of the nitrate that finds it way into groundwater. Under irrigated conditions, nitrate leaching is a function of irrigation efficiency and spatial variability as well as fertilizer management, which makes assessment of the problem more complex.

**APPROACH:** Research is being conducted by taking soil samples from commercial fields before planting and after a crop has been harvested. Three transects are taken across each field with five samples taken in each transect. Spacing of samples along the transect was based on the length of the run. The first sample was taken 10% of the run length from the top of the field. The next four samples were taken 20% of the run length apart. A 2-m by 2-m area is amended with KBr before the start of the growing season so that the depth of penetration of that season's irrigation water can be determined. The positions in the transect are numbered from one to five starting at the upper end of the field. Samples are taken to a depth of 270 cm and analyzed for ammonium, nitrate, bromide, chloride, and texture. Water samples are taken from each irrigation and the concentrations of chloride, nitrate, and ammonium determined. Chloride values in the soil will be used to provide a crude estimate of actual evapotranspiration. In 1995, samples were taken from three fields on two farms. Two of the fields were planted to cotton and the other to spinach. Two of the fields have no runoff, and the third is sloping with runoff. In the third field, flumes were installed to allow measurement of water entering and leaving the field. Automated data collection systems were operated during each irrigation during the 1995 growing season for cotton.

**FINDINGS:** Both of the farms monitored in 1995 were in the Maricopa-Stanfield Irrigation and Drainage District (MSIDD). Each water delivery point in the district has a system that determines the total amount of water delivered at each point. The field with runoff was not the only field served by the delivery point for the field, which required the use of flumes in the incoming ditch as well as the runoff channel. The other fields were the only ones served by their respective delivery points; and, since there was no runoff on those fields, we used the MSIDD values recorded by the producer after each irrigation to determine the water applied to the field. For the field where detailed information is available, the effect of having two irrigators can be seen as differences in inflow that follow approximately 12-hour cycles (fig. 1). The rates of inflow change from one irrigator to another and result in nonuniformity in the application. While this level of data is not available for the second farm, some of these effects are assumed to have occurred there as well.

The profiles of residual $NO_3$-N are variable within the same field. In some cases $NO_3$-N is low throughout the profile over the full length of the field (fig. 2), while in others, the concentration profiles $NO_3$-N show that leaching has occurred (figs. 3 and 4). In the case field, A3C leaching occurred at various locations in some transects, while in field A10, most of the leaching occurred at the low end of the field

**INTERPRETATION:** Based on the observations made during the growing season, uniformity of application, especially in sloped fields, is poor. This is a result of both soil variation and application differences. Because at least two irrigators—oneat night, one during the day—differences in application occurred. Length of run and soil variability both affected movement of nitrate. In the case of field A3C, the producer did a good job of managing the water and nitrogen inputs, but as seen in figure 3, soil variations caused problems in some areas of the field. Results of textural analysis show that sandy spots are the likely cause of the leaching in this field. In field A10, however, the pattern of leaching suggests that the length of run may be responsible for the deep penetration of the $NO_3$-N. In this field, water collects at the end of the field, resulting in deeper penetration of the water.

**FUTURE PLANS:** In 1996, the study will be expanded to include additional producers in the Yuma area. Selection of additional sites will be based on the crop rotations, soil type, and irrigation method.

**COOPERATORS:** B. Ekholt, Pinal County Irrigation Management Service; T. L. Thompson, University of Arizona Dept. of Soil and Water Science.

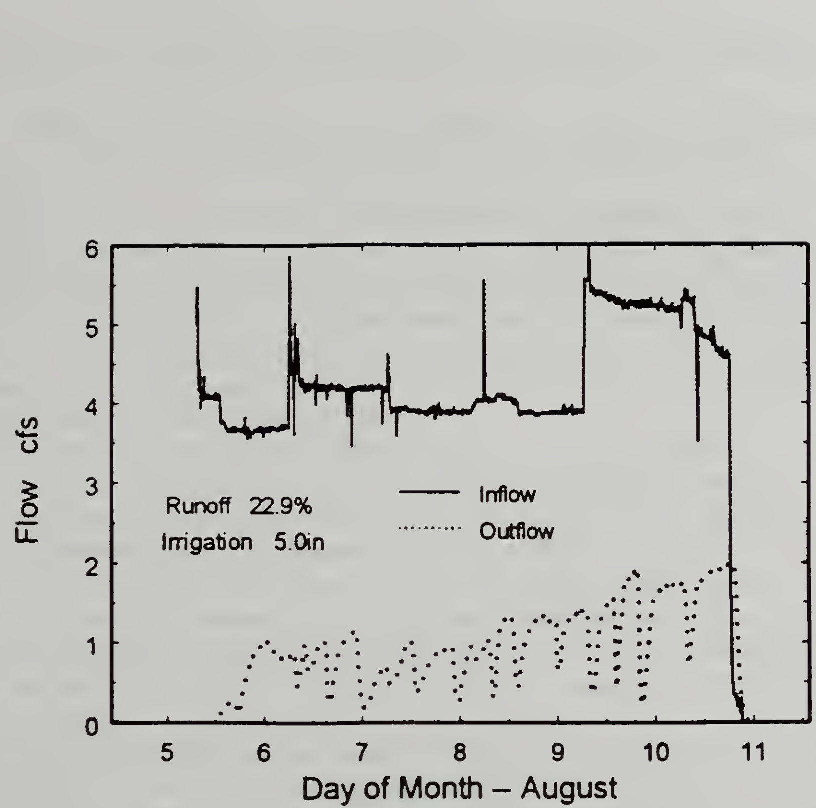


Figure 1. Example of water inflow and runoff for field 1-OL for the irrigation starting August 5, 1995, and ending August 11, 1995.

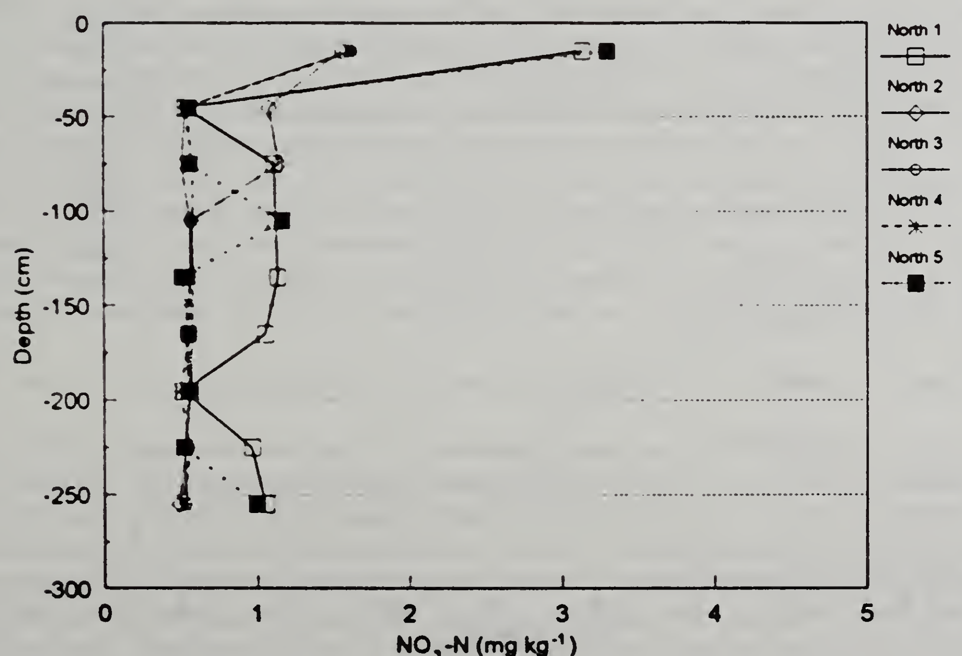


Figure 2. Profile of residual $NO_3$-N in the soil in field A3C in the north transect for five locations with location 1 being the head of the field.

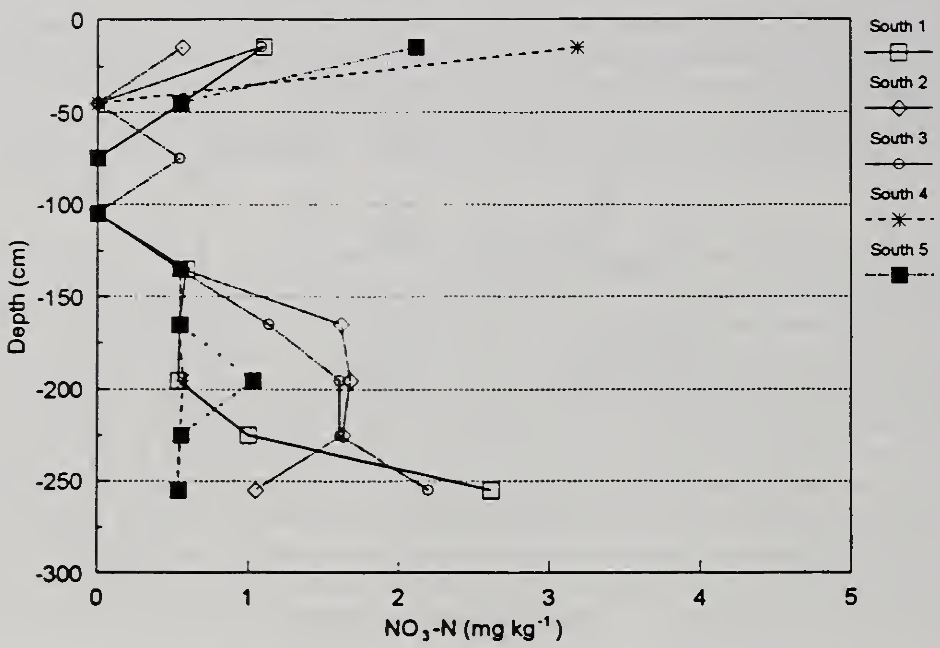


Figure 3. Profile of residual $NO_3$-N in the soil in field A3C in the south transect for five locations with location 1 being the head of the field.

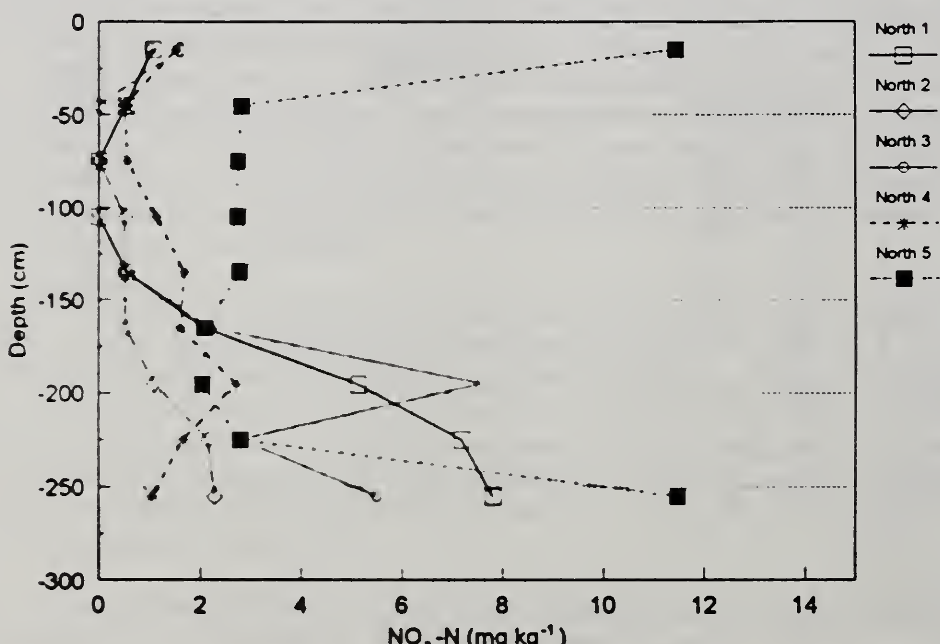


Figure 4. Profile of residual $NO_3$-N in the soil in field A10 in the north transect for five locations with location 1 being the head of the field.

## SIMULATION OF CHEMICAL TRANSPORT IN SOILS FROM SURFACE IRRIGATION

T.S. Strelkoff, Research Hydraulic Engineer; F.J. Adamsen, Soil Scientist;
and A.J. Clemmens, Supervisory Research Hydraulic Engineer

**PROBLEM:** Irrigation management influences the quality of both surface and groundwater supplies. Chemigation introduces agricultural chemicals into the irrigation water. Initially clean irrigation water picks up agricultural chemicals and naturally occurring minerals, some toxic, from the surface of fields and from contact by percolation through the porous soil medium. Nitrogen, chlorinated organic compounds, and heavy metals, for example, brought to farm fields in the course of agricultural operations; and naturally occurring chemicals, like selenium, can be transported to surface or subsurface water supplies by the movement of irrigation water, to the detriment both of human consumers of the water resource and wildlife dependent on these bodies of water.

The transport, transformation, and ultimate fate of chemical components of the irrigation water depend on the quantities of water remaining in the root zone after the irrigation, the quantities running off the end of the fields into drainage ditches and canals, and the quantities that continue to percolate through the soil, entering eventually either a groundwater aquifer or a river fed from groundwater seepage. The chemical and physical reactions between the water, the soil medium, and the particular chemicals involved significantly influence the transformation and ultimate fate of the chemical constituents. *Fingering* of the water front advancing downward through the soil medium occurs both as the result of nonhomogeneous soil, with worm and root channels, and layering of soils with a layer of low permeability overlying one of great permeability. This results in more rapid transport of waterborne constituents to the groundwater table than with reasonably homogeneous soils.

In the porous subsurface medium, many existing models view variation in only one dimension, the vertical, assuming no movement parallel to the stream flow. However, *interflow* is known to occur, especially on steep slopes and, in fact, provides a means of transport of groundwater, along with its chemical constituents, into surface streams.

The goal of this research effort is a predictive tool, a computer model, capable of simulating the transport and fate of chemicals, and thus capable of predicting the chemical response of a given agricultural field and its geologic site to one or another irrigation-management practice. Computer simulations would allow comparisons among various trial management modes in a program to seek optimum solutions. This would make possible recommendations on the basis of environmental considerations as well as upon water conservation and crop yield.

**APPROACH:** Two different problems comprise the subject of investigation: (1) transport of a contaminant by irrigation water from a contaminated soil-surface layer to stream flow and to the groundwater via deep percolation, and (2) the distribution of a chemical introduced nonuniformly with the irrigation inflow, e.g., a pulse of chemical introduced at some time after the start of irrigation. Both problems are to be treated by a plane two-dimensional (longitudinal and vertical) mathematical simulation, coupling a solution of the turbulent Navier-Stokes equations augmented with a two-equation turbulence model in the surface stream to a solution of the equations for unsaturated flow in a porous medium in the underlying soil. The two regions share a common vertical velocity field at the interface.

Mass transport is modeled in the entire system through dispersivities calculated from the flow equations. Sorption and desorption are incorporated in terms of both equilibrium and nonequilibrium kinetics of semi-empirical determination. The same is true for volatilization, degradation, and leaching processes, incorporated as sink terms in the mass transport model.

A physical model with a graded sand bed is to be used for verification of the mathematical model.

**FINDINGS:** The hydrodynamic portion of the simulation model has been completed, accuracy and conservation properties established, and comparisons with an existing depth-averaged model made and documented (Bradford and Katopodes, *in press*$_1$). Figure 1 shows sample pressure and velocity distributions in the surface flow and in the soil medium a few seconds after initiation of irrigation stream advance. Figure 2 is a picture of a velocity pattern with a soil possessing an artificially high permeability to exaggerate the velocity magnitudes within the soil medium.

A significant theoretical discovery was made regarding the unsaturated-soil-flow model component and its mass transport counterpart. The cause of spurious modes near the wetting front has been identified and a method for their removal implemented (Bradford and Katopodes, *in press*$_2$).

A model based on the turbulence characteristics of the flow has been developed for predicting the flocculation, settling, deposition, and erosion of cohesive sediments. The shear rates and kinetic energy of the hydrodynamic model are used for the calculation. The model has been validated for five different grain sizes on the basis of published experiments.

Numerous hypothetical runs involving chemical transport have been made using a complete geo-bio-chemistry module based on published reaction rates. No validation has been possible as yet.

Several experiments have been performed with the laboratory sand-bed flume. Initial experiments involved the use of dye solutions to allow visualization of flow behavior in the flume. The results showed that after a period of time, the flow was generally uniform. A set of experiments were then conducted to examine mass transport of solute between surface flow and soil-pore water. Bromide was used as the tracer in two scenarios. (1) The soil profile (3 inches deep) was saturated with a solution of $CaCl_2$; a solution of $CaBr_2$ was then introduced as a surface flow. Solution samples were collected from the soil and analyzed with colorimetry to determine mass transfer of Br from the surface stream to the soil water. The two solutions were matched for density. Scenario (2) was the reverse of (1); the soil profile was saturated with a $CaBr_2$ solution, and then a solution of $CaCl_2$ was introduced into the surface stream to induce transfer of Br out of the soil profile. Both sets of experiments showed behavior indicative of uniform, steady surface flow with diffusive mass transfer of Br in response to concentration gradients between the surface flow and the soil-pore water. Figure 3, for scenario (2), shows the reduction in Br at three different depths within the soil profile.

INTERPRETATION: The simulation model is ready for comparisons with physical experiments in the flume. It shows promise for simulating the chemical transport by surface irrigation to a useful degree. With increased use and verification, it should serve both as a research tool in evaluating one or another irrigation management practice and as a theoretical base for more approximate, more practical simulations.

FUTURE PLANS: The timing of future plans depend upon the extent of funding available. The mathematical model will be exercised over a range of practical conditions to establish and strengthen its reliability. Specific chemical constituents to be incorporated into the model will be selected, along with currently available figures on reaction kinetics. The physical flume and mathematical model will be operated under mutually equivalent conditions to test the various model assumptions, establish appropriate values for numerical solution parameters, and verify performance.

COOPERATORS: N.D. Katopodes, University of Michigan; M.L. Brusseau and P.M. Waller, The University of Arizona.

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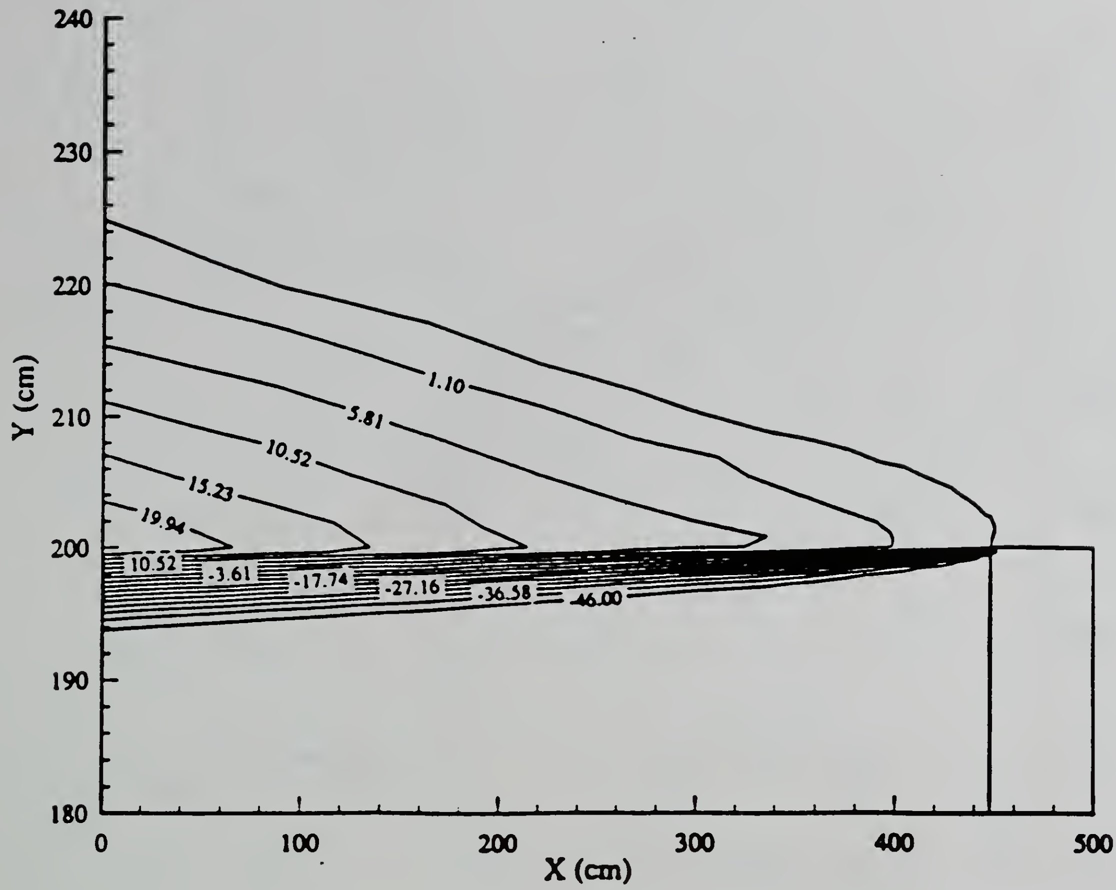


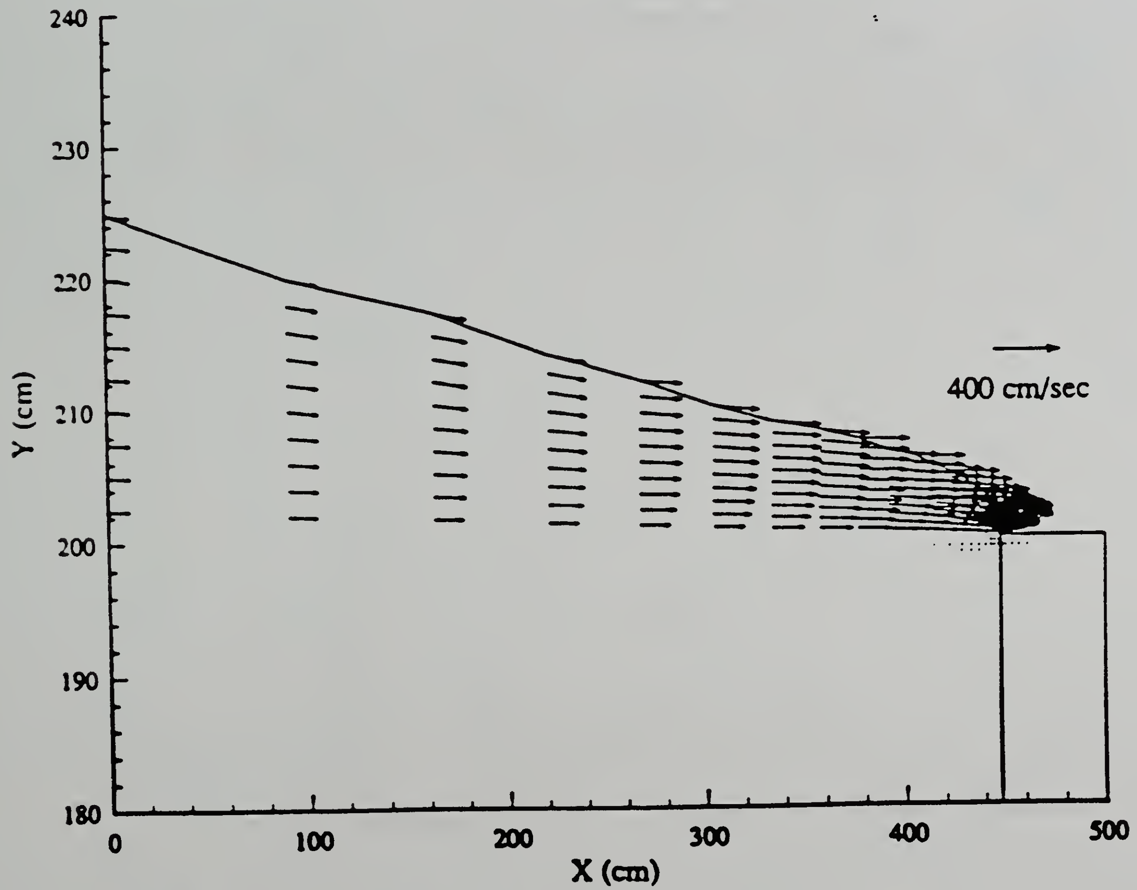


Figure 1. Pressure and velocity fields at $t = 1.5$ seconds. Unit inflow is 0.5 $m^2/s$.

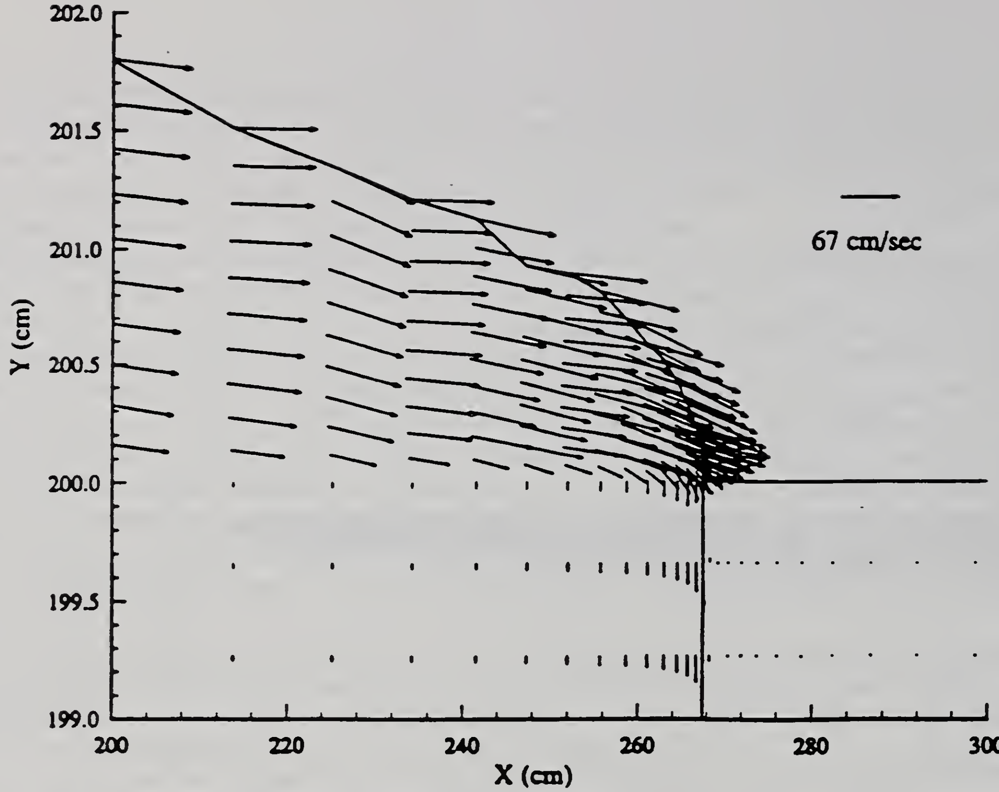


Figure 2. Velocity field with exaggerated soil permeability.

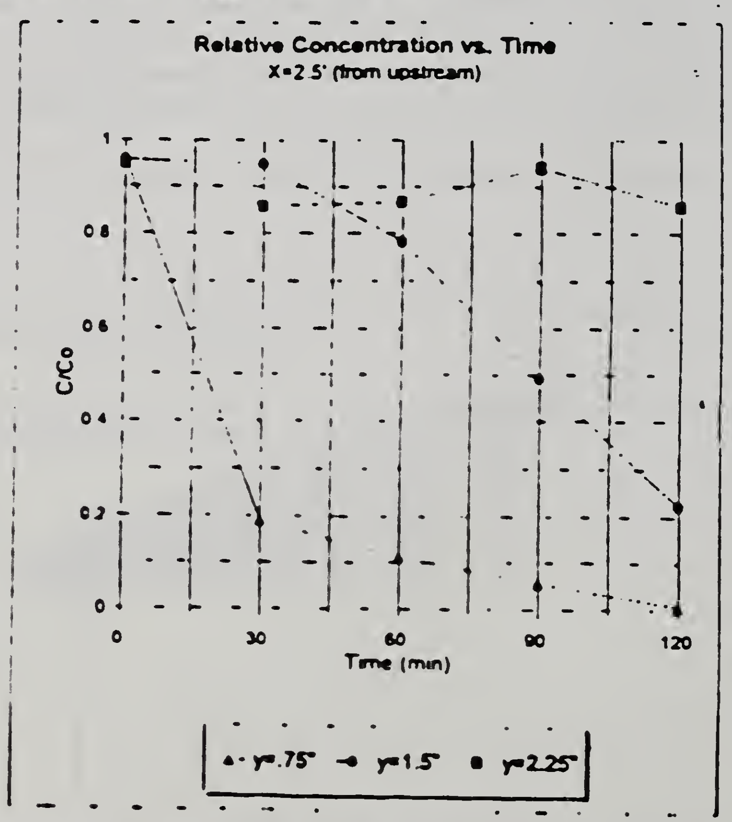


Figure 3. Reduction in Br concentrations in soil-pore water with time at various depths.

# PLANT GROWTH AND WATER USE AS AFFECTED BY ELEVATED $CO_2$ AND OTHER ENVIRONMENTAL VARIABLES

# AIRBORNE IMAGERY PRODUCTS FOR FARM MANAGEMENT

T.R. Clarke, Physical Scientist; M.S. Moran, Physical Scientist; J. Qi, Physical Scientist;
T.A Mitchell, Engineering Technician; P.J. Pinter, Jr., Research Biologist;
and E.M. Barnes, Agricultural Engineer

**PROBLEM:** Airborne imagery of farms has long held the potential of improving management practices simply by offering a new perspective from which to view the land. Until very recently, the only advancement from standard panchromatic or color aerial photography has been the use of color infrared film, with its increased sensitivity to vegetation. While this imagery has been useful to farm managers, the expense of procuring the images has not often been justified by the results: that is, the cost has exceeded the benefits.

**APPROACH:** The data collected during the Multispectral Airborne Demonstration over the Maricopa Agricultural Center (MADMAC) in 1994 provided the means to test algorithms developed to increase the value of multispectral imagery to the end user. The three products selected for immediate testing were a growth rate image ($\Delta$VI), which mapped the change in reflectance-based spectral vegetation index (VI) over time; a water deficiency index (WDI) which maps relative evapotranspiration using the VI/thermal trapezoid (Moran et al., 1994), and a crop stress index (CSI), an adaptation of the WDI that can detect abnormally warm plant canopies; a condition often caused by insufficient soil moisture.

**FINDINGS:** While analysis of the imagery from the fourteen MADMAC overflights is only partially complete, early results have been very encouraging. Growth rate images clearly show cotton fields with differing growth rates, and within-field variations were also apparent (fig. 1). Farm managers could use this information during the growing season to compare and adjust management strategies. The WDI evapotranspiration images (fig. 2) showed areal differences in water use, demonstrating the algorithm's potential for improving irrigation scheduling models. The CSI (Figure 3) showed areas with water stress before the effects were visible to the eye.

**INTERPRETATION:** Some difficulty has been encountered in geographic registration of the images, which has slowed production of finished images. This problem is particularly acute in the relative growth rate maps, where images from successive overflights must be mapped accurately before comparison. While this problem ultimately must be resolved through the development of better platform hardware, manual registration of the MADMAC data set is continuing.

The VIT Trapezoid vertices calculated using air temperatures and humidities from the local AZMET station appear to underestimate the temperatures seen in the thermal imagery. Resolving the problem is necessary to improve the reliability of such imagery.

**FUTURE PLANS:** As more of the MADMAC imagery is made ready for final analysis, we hope to expand cooperation with other researchers who were conducting experiments at MAC during the 1994 season, including cotton variety tests, insect and weed studies, and fertilization timing. We also will be working to improve our contacts with growers, extension personnel, and potential service providers to give us a better understanding of their needs and to give them an idea of possible benefits remote sensing can provide.

**COOPERATORS:** Christopher Neale, Utah State University; Roy Rauschkolb, Robert Roth, Pat Murphree, and MacD Hartman of The University of Arizona Maricopa Agricultural Center; Scott Miller, ARS Tucson; and Charles Sanchez, The University of Arizona Cooperative Extension.

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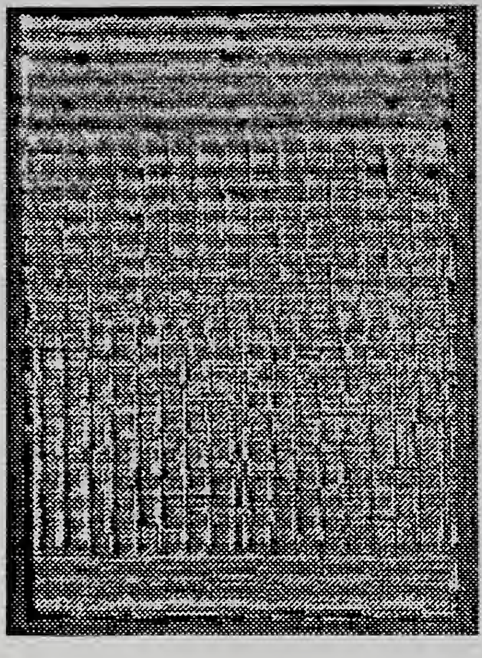

Figure 1. ΔVI image of a 9-hectare cotton field, showing the relative growth from July 6 to July 21, 1994. Lighter shades indicate faster growth. Note that the bottom border showed a greater change in vegetation index than its neighbor.

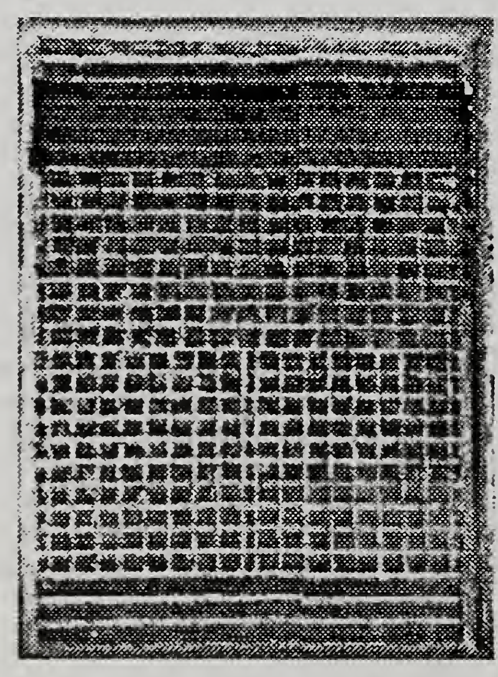

Figure 2. WDI image of the same field (Field 7) on July 6, 1994. Darker shades indicate higher ET. An irrigation was in progress near the top but had not yet reached the top border.

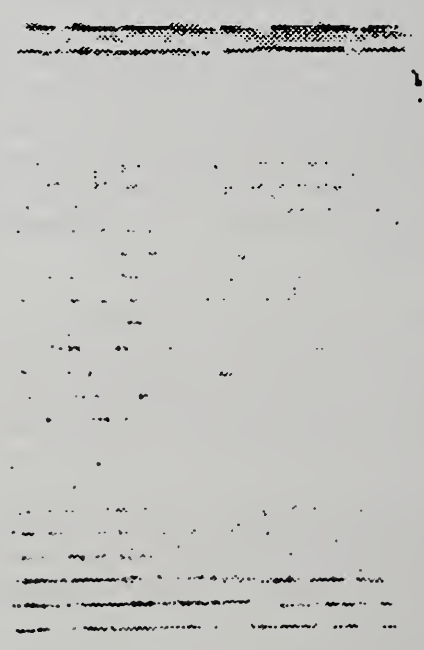

Figure 3. CSI image of Field 7 on July 6, 1994. Darker shades indicate warmer plant canopies. The top border showed mild stress.

# PHOTOSYNTHESIS AND CONDUCTANCE OF SPRING WHEAT LEAVES GROWN IN A FREE-AIR $CO_2$ ENRICHED (FACE) ATMOSPHERE AND VARIABLE SOIL MOISTURE

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**PROBLEM:** Atmospheric carbon dioxide concentration ($C_a$) is predicted to almost double over the next century. An increase in $C_a$ can reduce stomatal conductance ($g_s$) (Ball, 1982) which will restrict the transport of $CO_2$ and $H_2O$ between the atmosphere and substomatal cavity within a leaf. Under $C_a$-enrichment, however, any restriction in $CO_2$ flux resulting from $C_a$-enrichment-induced lowering of $g_s$ is generally offset by the increase in $CO_2$ gradient between the atmosphere and substomatal cavity, so that the internal $CO_2$ concentration ($C_i$) is generally higher, rather than lower for $C_a$-enriched leaves. These compensatory factors, therefore, result in an increase, rather than a decrease in net $CO_2$ flux into the leaf for $C_a$-enriched compared to $C_a$-ambient plants. In contrast, because the vapor pressure deficit (gradient for water vapor flux between the leaf and atmosphere) is not significantly altered by $C_a$-enrichment, any $C_a$-enrichment induced restriction in $g_s$ can reduce water vapor flux. Furthermore, in addition to the impact of $C_a$ on transport processes, many $C_a$-enrichment studies have shown that an increase in photosynthesis (A) has been short-lived, so that the initial higher rates for $C_a$-enriched plants declined to their pre-exposure levels within a few days. This suggest that *down-regulation* or *acclimation* of the photosynthetic apparatus occurred under $C_a$-enrichment. Comparative studies have shown that down-regulation varies with species and with other aspects of the environment (Webber et al., 1995). An imperative exist, therefore, to elucidate the impact that such a future high-$CO_2$ world will have on the transport of $CO_2$ and $H_2O$ between the atmosphere and leaf and to determine whether any acclimation of the photosynthetic apparatus will occur in wheat. The objectives of this study were: 1) to characterize and quantify the diurnal and seasonal trends in A and $g_s$, and 2) to determine whether results support or conflict with current views on down-regulation of photosynthesis for a field-grown wheat crop in $C_a$-enriched air and variable soil moisture regimes.

**APPROACH:** A field study on a hard red spring wheat (*Triticum aestivum* L. cv. Yecora Rojo) crop was conducted in an open field at The University of Arizona Maricopa Agricultural Research Center, located 50 km south of Phoenix, Arizona (33.1 °N, 112.0 °W). Wheat seeds were sown into flat beds at 0.25-m row spacings on December 7-8, 1993 , at a plant population of 180 plants $m^{-2}$ (50% emergence occurred on December 28, 1993, and the crop was harvested on June 1, 1994). Following sowing, a FACE apparatus (Hendrey, 1993) was erected on site to enrich the $C_a$ of ambient air, presently at ~350 *μmol mol⁻¹* (CONTROL), to a $C_a$ of 550 *μmol mol⁻¹* (FACE) treatment level (main plot). A subsurface drip tape irrigation system supplied a full irrigation of 100% evaporative demand and a 50% reduction in water supply (split-plot) treatments (WET and DRY, respectively). Treatments, therefore, consisted of FACE-WET (FW), FACE-DRY (FD), CONTROL-WET (CW), and CONTROL-DRY (CD). A preplant application of nitrogen along with several chemigation applications provided a total of 233 kg $ha^{-1}$ N. A preplant application of ~55 kg $ha^{-1}$ $P_2O_5$ was also applied. Leaf gas exchange rates were measured with a portable closed-exchange (transient) system with a 250 $cm^3$ transparent assimilation chamber on the central portion of five fully expanded (ligule emerged) upper-canopy sunlit leaves (three replications) from predawn to dusk on five days day of year (DOY) 41, 69, 81, 95 and 123. These dates corresponded to physiological growth stages of 3-leaf, tillering, stem extension, anthesis, and grain filling.

**FINDINGS:** Significant *$CO_2$* effects occurred because A was consistently higher in FACE compared to CONTROL (fig. 1). Significant *Irr* effects occurred because A was consistently higher in WET compared to DRY. Diurnal trends in A generally followed a consistent order (FW > FD = CW > CD), but absolute differences amongst treatments varied depending on the phenology of the crop. Regardless of leaf type examined (sunlit or shaded), no major alterations in the quantity or composition of polypeptides within the photosynthetic apparatus were observed (Nie et al., 1995). Levels of steady-state concentration of m*RNA* encoding these proteins were also independent of $C_a$ level. The diurnal trends in A reported herein, support the premise that no apparent down-regulation of the photosynthetic apparatus occurred under $C_a$-enrichment throughout the lifespan of either a well-watered or water-stressed field-grown spring wheat crop with adequate nitrogen.

Significant *Irr* effects occurred because $g_s$ for leaves in the WET were consistently higher than for DRY (fig. 2). Simarilarly, significant *$CO_2$* effects occurred because $g_s$ was consistently higher in CONTROL compared to FACE. Although diurnal trends in $g_s$ generally followed a consistent order (CW > FW = CD > FD), which was the inverse of the

order for A; again, as with A, the absolute differences among the treatments varied depending on the phenology of the crop.

**INTERPRETATION:** During a greater proportion of the growing season, A was highest in $C_a$-enriched well-watered and lowest in $C_a$-ambient water-stressed leaves. The $C_a$-enriched water-stressed and $C_a$-ambient well-watered leaves were always intermediate in their response, suggesting that the direct effect of future elevated $CO_2$ concentration will compensate somewhat, if not fully, for water stress in future drier climates, depending, of course, on the severity of any droughts. One reason a $C_a$-enriched water-stressed leaf maintained comparable A to that of a $C_a$-ambient well-watered one is because the steeper $CO_2$ gradient between $C_a$ and $C_i$ for a $C_a$-enriched leaf can offset reduction in A because of lower $g_s$ induced by either high $CO_2$ or water stress. Although, a $C_a$-ambient well-watered leaf had high $g_s$, thereby enabling potentially high $CO_2$ flux, the $C_a$ to $C_i$ gradient was lower for a $C_a$-ambient compared to $C_a$-enriched leaf. The result was compensatory ($CO_2$ equivalent to $H_2O$), so that a $C_a$-enriched environment can ameliorate for lower soil moisture.

The diurnal trends in $g_s$ were inversely related to A, as were the relative order in their treatment response. In contrast to A, the well-watered $C_a$-ambient and water-stressed $C_a$-enriched plants established the higher and lower physiological response, respectively, whereas the well watered $C_a$-enriched and water-stressed $C_a$-ambient were intermediate in their responses. This suggests that any reduction in $g_s$ due to $C_a$-enrichment was comparable to that due to water stress. The lower level of $g_s$ for $C_a$-enriched leaves under water stress occurred because of an additive effect. That is, water stress and higher $C_a$ can both independently reduce $g_s$. So combined, they could cause a further reduction in $g_s$, thereby estabishing the lowest treatment response. Similarly, the highest level for $g_s$ in well-watered leaves grown under $C_a$-ambient occurred because of an additive effect (the inverse of the aforementioned one, however). That is, well-watered and lower $C_a$ both independently increased $g_s$. So combined, they would cause a further increase in $g_s$, thereby establishing the highest levels in treatment response.

**FUTURE PLANS:** A FACE wheat experiment is scheduled for the 1994-95 and 1995-96 growing seasons. The experimental design will have similar $CO_2$ treatment levels as the previous two FACE wheat experiments, but the split-plot irrigation treatment will be replaced with nitrogen levels (high and low, respectively). Future research will quantify the gas exchange properties of wheat under open-field conditions with high $C_a$ and adequate and reduced levels of soil nitrogen to determine whether any *down-regulation* or *acclimation* of the photosynthetic apparatus will occur under nitrogen limited environmental conditions.

**COOPERATORS:** Operational support was contributed by the Carbon Dioxide Research Program of the Office of Health and Environmental Research of the Department of Energy and by the Postdam Institute for Climate Impact Research, Postdam, Germany. We also acknowledge the helpful cooperation of Roy Rauschkolb and his staff at The University of Arizona Maricopa Agricultural Center. The FACE apparatus was furnished by Brookhaven National Laboratory, and we are grateful to their representatives Keith Lewin, John Nagy, and George Hendrey for assisting in its installation and consulting about its use. This work contributes to the Global Change Terrestrial Ecosystem (GCTE) Core Research Programme, which is part of the International Geosphere-Biosphere Programme (IGBP).

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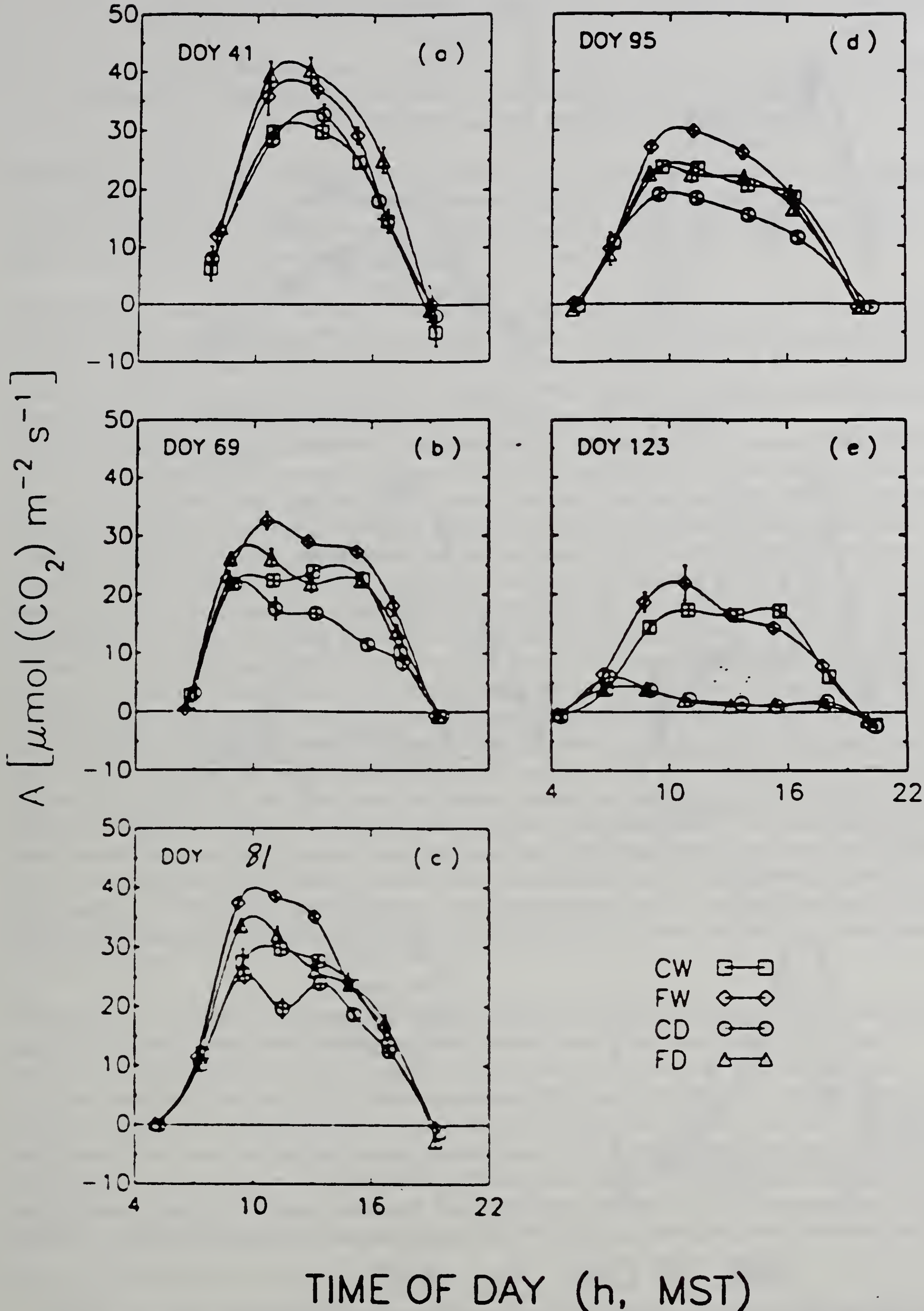


Figure 1. Diurnal trends in net assimilation rate (A) in fully-expanded sunlit wheat leaves for day of year (DOY) given during the 1994. Means composed of five leaves for three replications. Error bars given represent one standard error from mean..

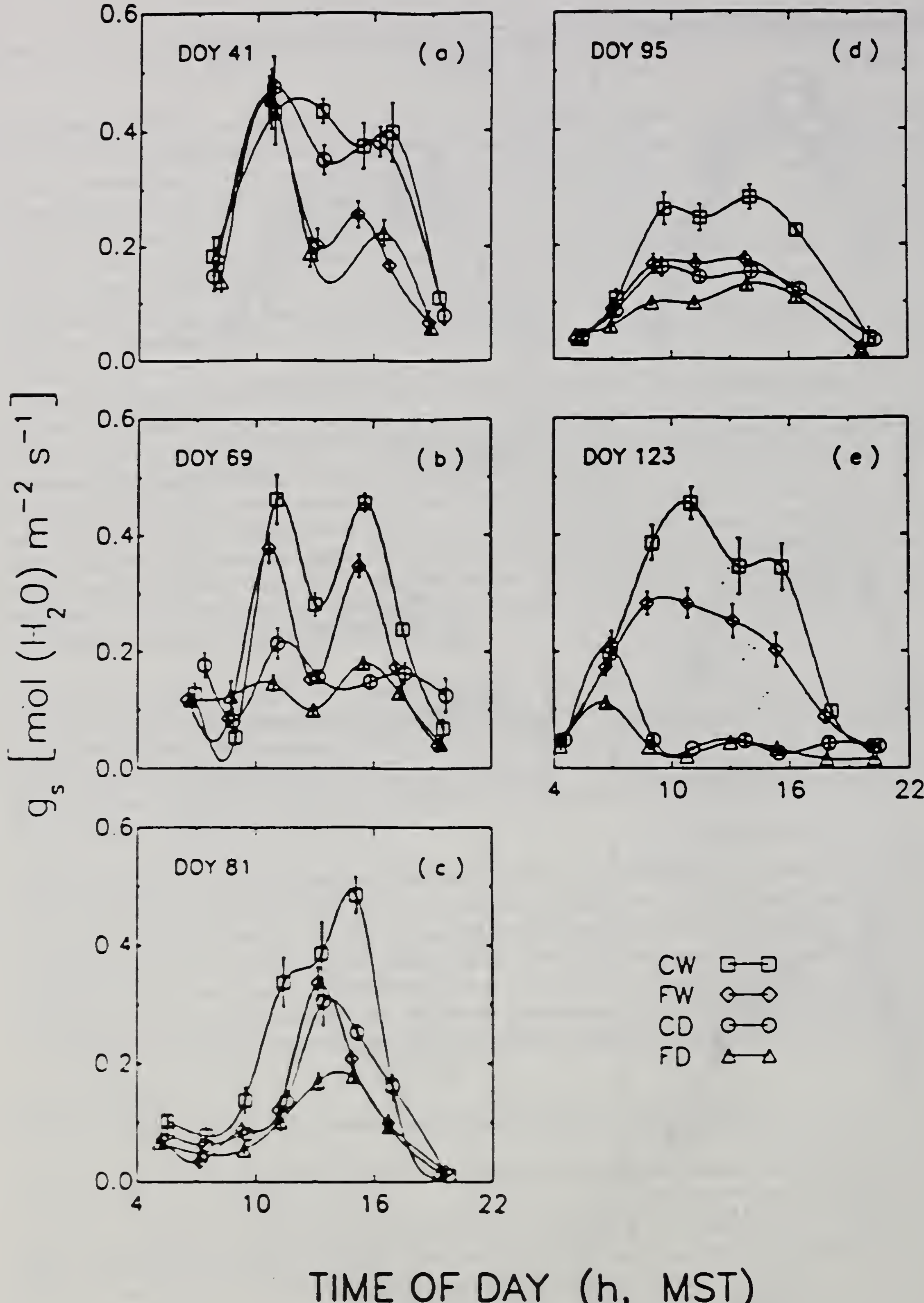


Figure 2. Diurnal trends in total stomatal conductance ($g_s$) in fully expanded sunlit wheat leaves for day of year (DOY) given during 1994. Means composed of five leaves for three replications. Error bars given represent one standard error from mean.

# PROGRESS AND PLANS FOR THE FREE-AIR $CO_2$ ENRICHMENT (FACE) PROJECT

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**PROBLEM:** The $CO_2$ concentration of the atmosphere is increasing and expected to double sometime during the next century. Climate modelers have predicted that the increase in $CO_2$ will cause the Earth to warm and precipitation patterns to be altered. This project seeks to determine the effects of such an increase in $CO_2$ concentration and any concomitant climate change on the future productivity, physiology, and water use of crops.

**APPROACH:** Numerous $CO_2$ enrichment studies in greenhouses and growth chambers have suggested that growth of most plants should increase about 30% on the average with a projected doubling of the atmospheric $CO_2$ concentration. However, the applicability of such work to the growth of plants outdoors under less ideal conditions has been seriously questioned. The only approach whose realism is unquestioned and which can produce an environment as representative of future fields as possible today is the free-air $CO_2$ enrichment (FACE) approach.

The FACE approach has been criticized because the prodigious quantities of $CO_2$ required make it expensive. A FACE experiment is expensive, but because of the relatively large area of the FACE plots, there is a huge economy of scale, so that per unit of treated plant material, FACE costs 1/4 or even less than the cost of other approaches. Thus, there is an economic incentive to have many scientists cooperate on large, comprehensive FACE experiments.

About 20 scientists from ARS, Brookhaven National Laboratory, and several universities have cooperated on a FACE project from 1989 to 1991 at the University of Arizona's Maricopa Agricultural Center (MAC). These experiments have yielded a wealth of information about the growth and physiological responses of cotton to elevated $CO_2$, at ample and limiting supplies of water, as reported in, *FACE: Free-Air $CO_2$ Enrichment for Plant Research in the Field*, edited by G. R. Hendrey, and in a special issue of *Agricultural and Forest Meteorology*, edited by W.A. Dugas and P.J. Pinter, Jr. Data sets in IBSNAT format suitable for validation of plant growth models have been prepared.

From December 1992 through May 1993 and from December 1993 through May 1994 two more FACE experiments were conducted, this time on wheat at ample and limiting levels of water supply. Fifty scientists from 25 different research organizations in eight countries have participated, measuring leaf area, plant height, abovegroundground biomass plus roots that remained when the plants were pulled, apical and morphological development, canopy temperature, reflectance, chlorophyll, light use efficiency, energy balance, evapotranspiration, soil and plant elemental analyses, soil water content, sap flow, root biomass from soil cores, photosynthesis, respiration, stomatal conductance, leaf water potential, carbohydrates, photosynthetic proteins, antioxidants, stomatal density and anatomy, digestibility, decomposition, grain quality, soil $CO_2$ fluxes, and changes in soil C storage from soil and plant C isotopes. All of the data will be assembled in a standard format for validation of wheat growth models. Seven collaborating wheat growth modelers plan to utilize the data.

**FINDINGS:** It is beyond the scope of this report to review the results presented in the abovegroundmentioned book, paper, and numerous manuscripts. Briefly however, averaged over three years, cotton yields were increased about 40% with $CO_2$ concentrations elevated to 550 ppm, and there was no significant increase in water use.

Analyses of the data from two FACE Wheat experiments (1992-3 and 1993-4) are not complete although 28 manuscripts have been prepared, and 16 are published or in press in a variety of journals. However, the growth, morphological development, soil water balance, and energy balance aspects are reported in this volume[1] by Pinter et al., Wall et al., and Kimball et al. Briefly, wheat responded much differently than cotton to elevated $CO_2$. Early in the season in January and February when temperatures were cool, there was little response to $CO_2$ (concentrations of 550 $\mu$mol/mol and ambient). Then as temperatures warmed into spring, the FACE plants grew about 20% more than the CONTROL plants

[1]See "Seasonal Dynamics of PAR Absorption and Conversion Efficiency by Spring Wheat: Effects of Free-Air $CO_2$ Enrichment (FACE) and Water Stress" by Pinter et al., "Effects of Free-Air $CO_2$ Enrichment (FACE) on the Energy Balance and Evapotranspiration of Wheat" by Wall et al., Atmosphere and Under Variable Soil Moisture Regimes" by Wall et al., and "Effects of Free-Air $CO_2$ Enrichment (FACE) on the Energy Balance and Evapotranspiration of Wheat" by Kimball et al.

at ambient $CO_2$. The number of tillers per plant was increased from about 4 to 5. Then in May a surprising thing happened. The FACE plants matured and senesced earlier by 7-10 days than the CONTROLs, such that the extra growing time allowed the CONTROL plants to narrow the final difference to about 10% in the well-watered plots, while the difference remained at about 20% in the water-stressed plots. The FACE plants averaged 0.6°C warmer than the CONTROLs, day and night, all season long, in the well-watered plots, and we speculate that this temperature rise caused the earlier maturity. Water use was decreased slightly, 5 to 8%, as indicated by water and energy balance measurements.

INTERPRETATION: The increasing atmospheric $CO_2$ concentration should be beneficial to future cotton production and probably other indeterminate crops growing in warm climates, provided water supplies do not change significantly. However, cool-season determinate crops such as wheat probably will benefit also, but not as much. Irrigation requirements may be somewhat reduced for future wheat production, provided climate changes are minimal.

FUTURE PLANS: FACE wheat experiments at ample and limiting supplies of soil nitrogen will be conducted starting mid-December 1995 through May 1996 and again in 1996-7, funded by the Department of Energy through a grant to the University of Arizona. U.S. Water Conservation Laboratory personnel will be major collaborators on the project and will provide management support. To prepare for these upcoming experiments, in December 1994 the field at Maricopa was planted to a crop of oats which was removed from the field while green in order to withdraw as much nitrogen as possible from the soil, and the field was also leached with 15 cm of water in early December 1995. A feature of the 1995-6 experiment is that blowers are being added to the control plots to make them more like the FACE plots, and there will be two "ambient" plots with no blowers. Thus, we plan to evaluate the effect of these blowers on crop growth in addition to the main experiment of determining the interactive effects of varying $CO_2$ and soil N on wheat response.

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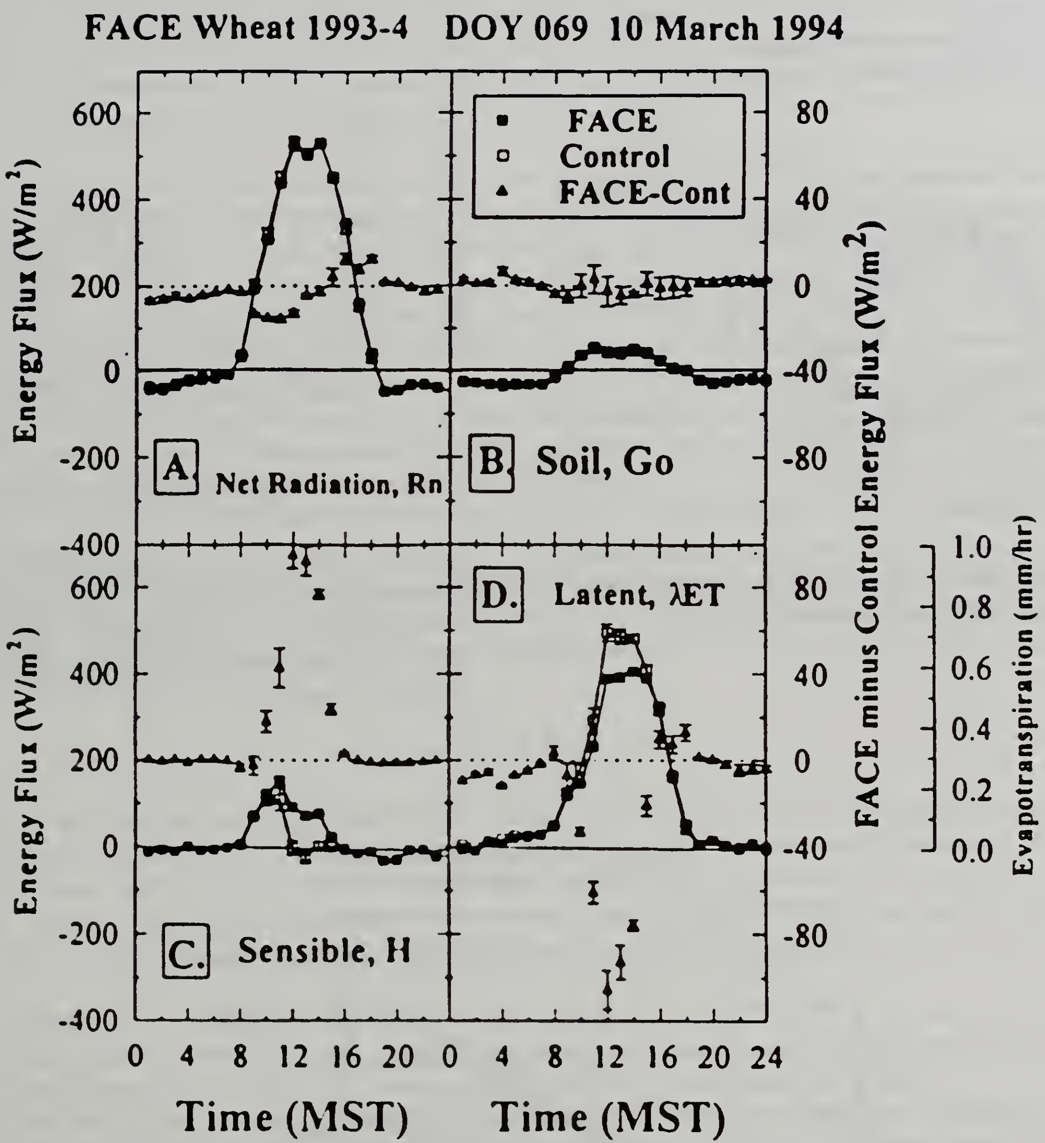


Figure 1. Net radiation, $R_n$ (A), soil heat flux, $G$ (B), sensible heat flux, $H$ (C), and latent heat flux, $\lambda ET$ (D) in CONTROL and FACE plots and their difference vs. time of day on 10 March 1994. Also, standard error, SE, bands are indicated.

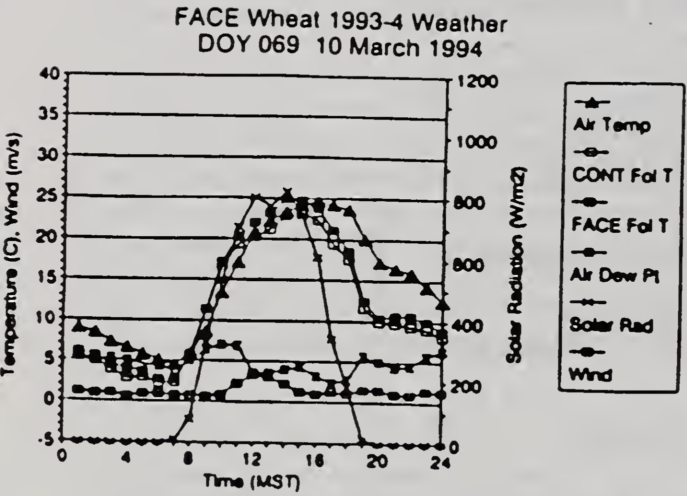


Figure 2a. Air dry bulb and dew point temperatures, foliage temperatures from FACE and CONTROL plots, wind, and solar radiation for March 10, 1994

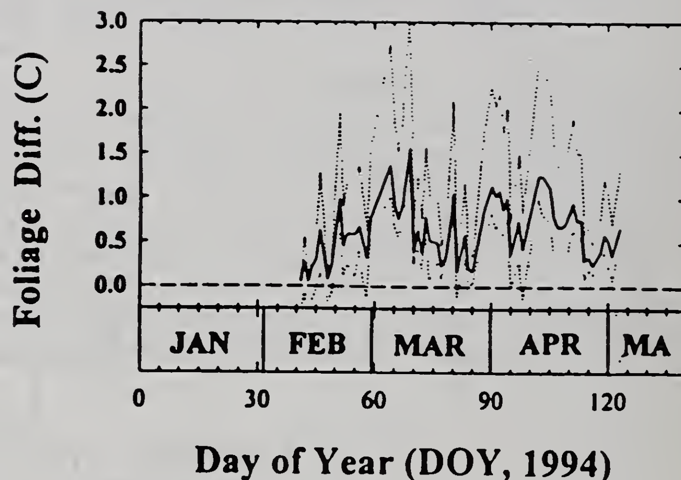


Figure 2b. Daily average foliage temperature difference between FACE and CONTROL plots versus day of year for 1994. Data are omitted from January when the infrared thermometers viewed soil and May when the crop was senescent.

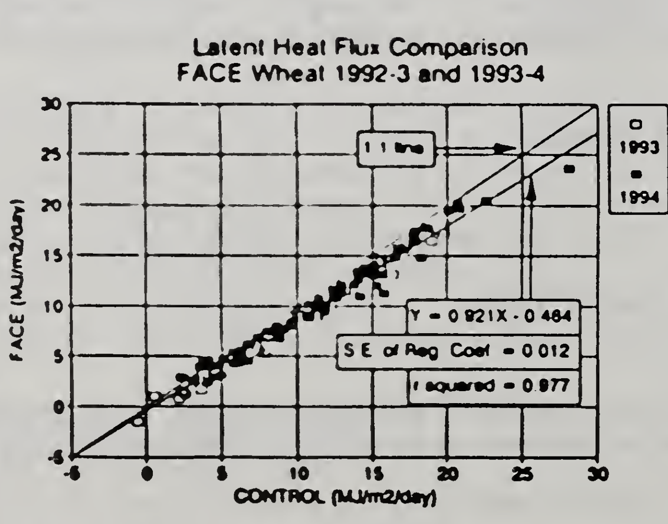


Figure 2c. Daily total FACE latent heat flux, λET for the combined data sets from February 1 through April 30, 1993, and February 10 through May 3, 1994. The regression excludes January data when the radiometers viewed soil and May data when the crop senesced.

# EFFECTS OF FREE-AIR $CO_2$ ENRICHMENT (FACE) ON THE ENERGY BALANCE AND EVAPOTRANSPIRATION OF WHEAT

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**PROBLEM:** The $CO_2$ concentration of the atmosphere is increasing and expected to double sometime during the next century. Climate modelers have predicted that the increase in $CO_2$ will cause the Earth to warm and precipitation patterns to be altered. Such increases in $CO_2$ and possible climate change could affect the hydrologic cycle and future water resources. One component of the hydrologic cycle that could be affected is evapotranspiration (*ET*), which could be altered because of the direct effects of $CO_2$ on stomatal conductance and on plant growth. One important objective of this experiment was to evaluate the effects of elevated $CO_2$ on the *ET* of wheat.

**APPROACH:** The evapotranspiration measurements were one component of the much larger Free-Air $CO_2$ Enrichment (FACE) project, which sought to determine the effects of elevated $CO_2$ on wheat growth, yield, and many physiological processes, as well as water use. Two experiments over the 1992-3 and 1993-4 growing seasons have been completed. In these experiments, four toroidal plenum rings of 25-m diameter constructed from 12" irrigation pipe were placed in a wheat field at Maricopa, Arizona, shortly after planting. The rings had 2.5-m-high vertical pipes with individual valves spaced every 2 m around the periphery. Air enriched with $CO_2$ was blown into the rings, and it exited through holes at various elevations in the vertical pipes. Wind direction, wind speed, and $CO_2$ concentration were measured at the center of each ring. A computer control system used wind direction information to turn on only those vertical pipes upwind of the plots, so that the $CO_2$-enriched air flowed across the plots, no matter which way the wind blew. The system used the wind speed and $CO_2$ concentration information to adjust the $CO_2$ flow rates to attain a near-constant 550 ppm by volume $CO_2$ concentration at the centers of the rings. Four matching CONTROL rings at ambient $CO_2$ but with no air flow were also installed in the field.

The determination of the effects of elevated $CO_2$ on *ET* by traditional chambers is fraught with uncertainty because the chamber walls that constrain the $CO_2$ also affect the wind flow and the exchange of water vapor. Therefore, a residual energy balance approach was adopted, whereby *ET* was calculated as the difference between net radiation, $R_n$, soil surface heat flux, $G_o$, and sensible heat flux, $H$:

$$\lambda ET = R_n - G_0 - H$$

$R_n$ was measured with duplicate net radiometers, and $G_o$ with soil heat flux plates. $H$ was determined by measuring the temperature difference between the crop surface and the air and dividing the temperature difference by an aerodynamic resistance calculated from a measurement of wind speed. The air temperature was measured with an aspirated psychrometer, and the crop surface temperature was measured with duplicate infrared thermometers (IRTs) mounted above each plot. The net radiometers and IRTs were switched weekly between the FACE and CONTROL plots.

**FINDINGS:** Figure 2A shows the hourly patterns of weather variables for one mid-season day, March 10, 1994. Foliage temperatures were typically about 3°C cooler than air temperatures except from dawn until shortly after noon. FACE foliage temperatures averaged 1.0 ±0.2 °C warmer than CONTROL temperatures on this day.

$R_n$ (fig. 1A) was the largest component of the energy budget of March 10, 1994, generally much larger in magnitude than $G_o$ (fig. 1B) or $H$ (fig. 1C). Consequently, $\lambda ET$ (fig. 1D) tended to follow $R_n$. The error bands on $R_n$ were tight, and differences in $R_n$ between FACE and CONTROL were small (fig. 1A). Consequently, effects of FACE on $\lambda ET$ also generally were small although on this particular day, FACE $\lambda ET$ averaged 17% less than CONTROL $\lambda ET$.

FACE tended to increase the wheat canopy temperatures by an average 0.6°C from February through April, which made the crop slightly less cooler than air temperature most of the time (fig. 2B).

Daily FACE $R_n$ averaged 3% less than CONTROL $R_n$ from February through April for both the 1992-3 and 1993-4 experiments (data not shown). Furthermore, the error bounds were tight with little evidence of changes in treatment effects when the instruments were switched weekly between FACE and CONTROL. Daily totals of $G_o$ were very small (generally < 1 MJ m$^{-2}$ day$^{-1}$), as expected. Daily FACE $H$ tended to be higher than CONTROL $H$ (fig. 1C), which meant it was less negative on some days. This tendency was because the FACE plants were slightly warmer than the

CONTROLs most of the time, and both FACE and CONTROL plants generally were cooler than the air except from about dawn until shortly after noon (fig. 2A).

Daily FACE $\lambda ET$ was less than that of the CONTROL plots most of the days in both experiments (fig. 2C). At the end of the seasons in May, the FACE plants matured earlier, leading to larger differences in $\lambda ET$. Excluding these May data, the regression of FACE on CONTROL $\lambda ET$ from February through April (fig. 2C) indicates that the FACE treatment decreased $\lambda ET$ by an average 8%.

**INTERPRETATION:** It appears from these data that irrigation requirements for wheat may be somewhat lower in the future high-$CO_2$ world (provided that any global warming is small).

Also, the observation that FACE caused foliage temperatures to be increased by 0.6°C day and night, all season long, may be the cause of the accelerated maturity and senescence of the plants in the FACE plots. This also suggests that the areas for optimum wheat production may shift somewhat due to just the increasing $CO_2$ concentration, whether global warming occurs or not.

**FUTURE PLANS:** Another FACE Wheat experiment will commence on about December 15, 1995, to evaluate the response of wheat to FACE when soil nitrogen is limited (See report on "Progress and Plans for the Free-Air $CO_2$ Enrichment (FACE) Project."). Micrometeorological parameters required to characterize the growing conditions in support of modeling efforts will be measured. Energy balance and $\lambda ET$ will be determined in two replicate blocks of the four treatments (high and low $CO_2$ and high and low N). In addition, the 1995-6 experiment will feature plots at ambient $CO_2$ with and without blowers like those used in the FACE plots for distribution of $CO_2$. Therefore, the effect of these blowers on energy balance and canopy temperatures will also be evaluated.

**COOPERATORS:** See report on "Progress and Plans for the Free-Air $CO_2$ Enrichment (FACE) Project."

## $CO_2$ ENRICHMENT OF TREES

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**PROBLEM:** The continuing rise in the $CO_2$ content of Earth's atmosphere is believed by many people to be the most significant ecological problem ever faced by humanity because of the widespread assumption that it will lead to catastrophic global warming via intensification of the planet's natural greenhouse effect. However, this belief is largely due to a lack of knowledge of the many beneficial effects of atmospheric $CO_2$ enrichment on Earth's plant life. Hence, it is imperative that this other aspect of atmospheric $CO_2$ be elucidated so that the public can have access to the full spectrum of information about the environmental consequences of higher-than-ambient levels of atmospheric $CO_2$. Only under such conditions of complete and wide-ranging understanding can the best decisions be made relative to national and international energy policies.

As forests account for two-thirds of global photosynthesis and are thus the primary players in the global biological cycling of carbon, we have chosen to concentrate on trees within this context. Specifically, we seek to determine the direct effects of atmospheric $CO_2$ enrichment on all aspects of their growth and development; and we hope to be able to determine the ramifications of these direct effects for global carbon sequestering, which may also be of considerable significance to the climatic impact of atmospheric $CO_2$ enrichment, as the biological sequestering of carbon is a major factor in determining the $CO_2$ concentration of the atmosphere and the ultimate level to which it may rise.

**APPROACH:** In July 1987, eight 30-cm-tall sour orange tree (*Citrus aurantium* L.) seedlings were planted directly into the ground at Phoenix, Arizona. Four identically-vented, open-top, clear-plastic-wall chambers were then constructed around the young trees, which were grouped in pairs. $CO_2$ enrichment–to 300 ppm above ambient–was begun in November 1987 to two of these chambers and has continued unabated since that time. Except for this differential $CO_2$ enrichment of the chamber air, all of the trees have been treated identically, being irrigated at periods deemed appropriate for normal growth and fertilized as per standard procedure for young citrus trees.

Numerous measurements of a number of plant parameters have been made on the trees, some on an hourly basis, some weekly, some monthly, and some annually. Results of our findings are summarized below, along with results of measurements made on some other plants grown beneath the orange trees and in two temperature-controlled greenhouses that were subdivided into two $CO_2$ treatments. Results of a large literature survey of the subject are also included.

**FINDINGS:**

(1) Over the course of our long-term sour orange tree study, we have measured the trunk circumference of each tree at the mid-point of each month; and from the end of the third year of the study, we have counted the number of oranges removed from all trees at the conclusion of each year's harvest. In connection with the last of these harvests, we also measured the diameter of every orange removed from each tree, along with the rind thicknesses of 240 randomly selected oranges from each of the two $CO_2$ treatments.

From these data we have developed a seven-year history of the growth-promoting effects of atmospheric $CO_2$ enrichment (see fig. 1). This history indicates that by the end of the second year of the study, the trunk plus branch volume of the $CO_2$-enriched trees was approximately 2.75 times greater than that of the ambient-treatment trees. Since that time, this factor has dropped to just under 2.0; but the decline in the $CO_2$ -enriched/ambient-treatment ratio of trunk plus branch volume has been nearly perfectly offset by the relative fruit production advantage enjoyed by the $CO_2$-enriched trees, which began to manifest itself in year 3 of the study. From year 2 through year 5, for example, the total trunk plus branch plus cumulative fruit rind volume of the trees exposed to the extra $CO_2$ was consistently about 2.77 times greater than the corresponding volume of the trees exposed to ambient air.

In years 6 and 7 of the experiment, however, a number of branches of the $CO_2$-enriched trees grew all the way to the walls of the enclosures; and many blossoms and young fruit were destroyed by intermittent physical trauma produced by the action of wind against the taut plastic, which reduced the fruit production of the $CO_2$-enriched trees from what it would have been had their branches not been adversely impacted by this horizontal space restriction. Hence, we will have to wait a few more years for this lateral growth obstruction–which is somewhat analogous to what occurs in a developing forest when neighboring trees begin to crowd each other–to occur to the same degree in the ambient-air chambers, in order to determine the long-term effects of atmospheric $CO_2$ enrichment in a spatially-confined environment.

For the present, we find no compelling evidence for any acclimation of the $CO_2$-enriched trees that might reduce their enhanced productivity in an unobstructed setting. Indeed, even in the face of the spatial limitation created by the enclosure walls, the $CO_2$-enriched trees continue to extend the time interval it would take the ambient-treatment trees to attain the

same level of cumulative biovolume production; while annual productivity data suggest that the growth rates of the trees of both $CO_2$ treatments (which currently differ by a factor of two) are probably within only a couple of years of reaching their asymptotic upper limits characteristic of maturity. Hence, we have reason to believe that the $CO_2$ -induced growth stimulation will be manifest throughout the entire life span of the trees.

(2) At weekly intervals throughout years 4 through 7 of the sour orange tree study, we measured chlorophyll a contents of 60 leaves on each of the eight trees with a hand-held chlorophyll meter that was specifically calibrated for the trees of our study. At bi-monthly intervals we also measured the areas, dry weights and nitrogen contents of 68 leaves from each tree. Expressed on a per-unit-leaf-area basis, and averaged over the four-year period, leaves from the four $CO_2$-enriched trees contained 4.8% less chlorophyll and nitrogen than leaves from the four ambient-treatment trees (see fig. 2). However, based on an empirical relationship we had previously developed between trunk cross-sectional area and the number of leaves on a tree, along with the results of a previously published study of $CO_2$ effects on leaf size, we calculate that the total chlorophyll a and nitrogen contained in all the leaves of the $CO_2$-enriched trees averaged 75% more than the total chlorophyll a and nitrogen contained in all the leaves of the ambient-treatment trees over the four-year course of the study. It is interesting to note that this percentage enhancement is identical to the percentage increase in atmospheric $CO_2$ concentration experienced by the $CO_2$-enriched trees. With only two $CO_2$ treatments, however, we cannot say whether this exact correspondence is anything more than coincidence.

(3) Net photosynthetic rates of individual sour orange tree leaves were measured on a number of summer afternoons over the past several years, when air temperatures were extremely warm. In the trees exposed to the extra 300 ppm of $CO_2$, the upper-limiting temperature—above which net photosynthesis becomes negative—was approximately 7°C higher than it was in the ambient-treatment trees (see fig. 3). This ability of the $CO_2$ -enriched trees to grow and sequester carbon at higher temperatures than can be tolerated under current $CO_2$ concentrations led to a 75% enhancement in the net photosynthesis of the $CO_2$-enriched trees at a temperature of 31°C, a 100% enhancement at 35°C, and a 200% enhancement at 42°C.

(4) Uniform rooted cuttings of Eureka lemon trees were grown for six months in pots in two glasshouses that were programmed to provide moderate (29/21°C day maximum / night minimum) or high (42/32°C day maximum/night minimum) air temperatures. Each of the glasshouses was further subdivided to provide two $CO_2$ treatments: ambient and ambient plus 300 ppm $CO_2$. In the moderate air temperature treatment, elevated $CO_2$ increased growth by approximately 21%; while in the high air temperature treatment, it produced an 87% increase in growth. Under the high air temperature regime, the $CO_2$-enriched leaves also contained about 15% more chlorophyll than the ambient-treatment leaves. Consequently, and as with the sour orange trees, atmospheric $CO_2$ enrichment significantly reduced the negative effects of high-temperature stress on shoot growth.

(5) In yet a third investigation of the interactive effects of $CO_2$ and temperature, we measured total biomass production in twelve different harvests of three plantings of 424 Agave vilmoriniana plants (a common desert succulent with CAM physiology) that we grew in our large $CO_2$ enrichment chambers beneath the sour orange trees over a period of four years. Once again, the growth stimulation provided by the extra 300 ppm of $CO_2$ was found to be greater at higher temperatures, ranging from 28% at 19°C to 51% at 29°C (see fig. 4).

(6) In preparation for the Third Annual Kuehnast Lecture of the Department of Soil, Water and Climate at the University of Minnesota, one of us (S.B. Idso) reviewed over 350 scientific journal articles related to $CO_2$ and global change. This exercise resulted in the publication of a small booklet entitled "$CO_2$ and the Biosphere: The Incredible Legacy of the Industrial Revolution," which summarizes the results of hundreds of laboratory and field experiments that demonstrate that as the air's $CO_2$ content and the deposition of anthropogenically-produced nitrogen and other nutrients have risen in phase with the industrial development of the past two centuries, so also, as a direct consequence of those phenomena, has the vitality of earth's biosphere increased, where man has not damaged it directly by overt actions, such as deforestation or localized pollution.

**INTERPRETATION:** The implications of our findings have a direct bearing on the current debate over anthropogenic $CO_2$ emissions. They demonstrate that $CO_2$ is an effective aerial fertilizer, enhancing plant growth under nearly all conditions.

**FUTURE PLANS:** We anticipate continuing the sour orange tree experiment for several more years, focusing on the effects of atmospheric $CO_2$ enrichment on fruit production. We also plan to study $CO_2$ effects on a number of other plants.

**COOPERATORS:** U.S. Department of Energy, Atmospheric and Climate Research Division, Office of Health and Environmental Research.

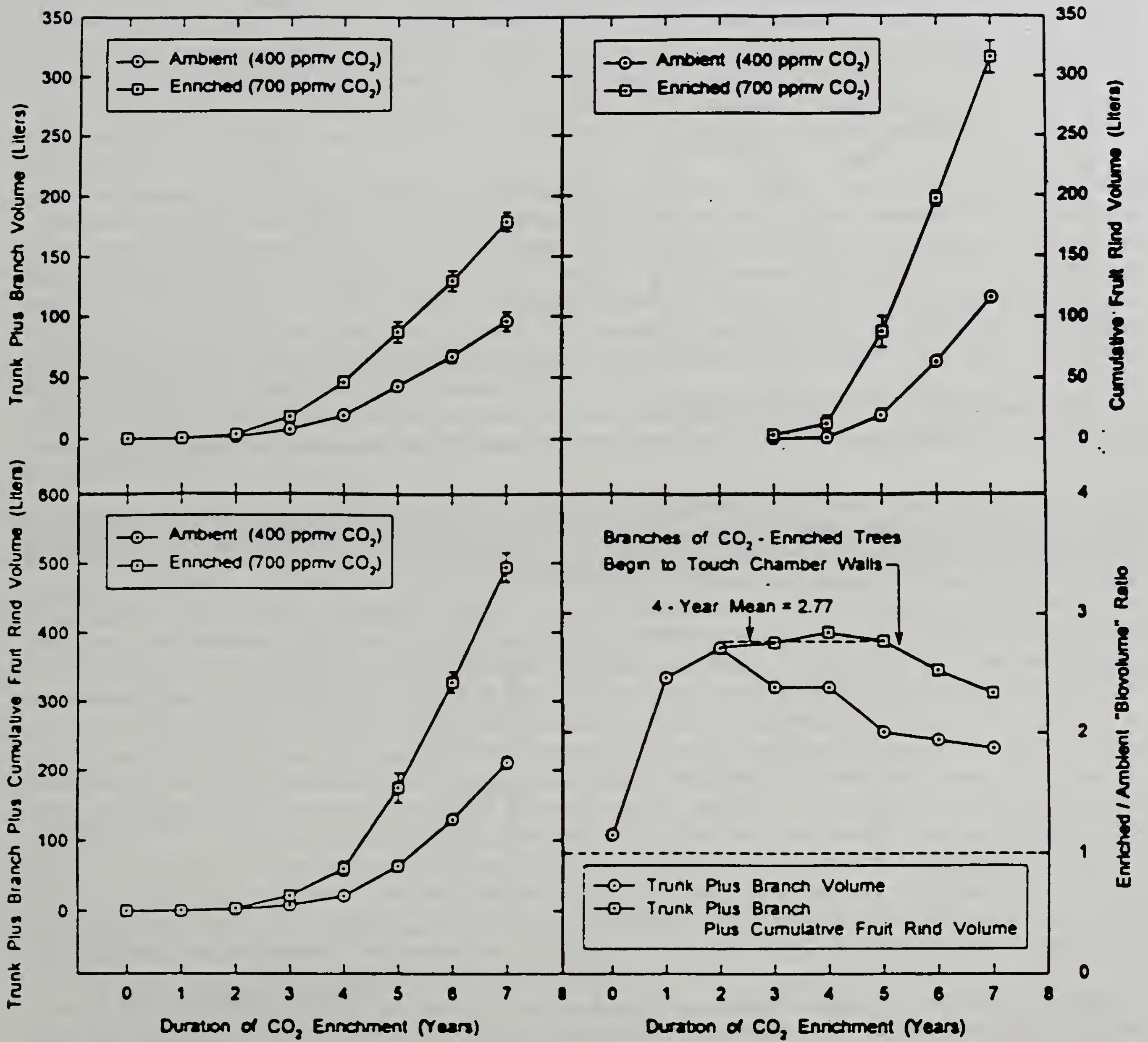


Figure 1. Seven-year histories of trunk plus branch volume (upper left), cumulative fruit rind volume (upper right), trunk plus branch plus cumulative fruit rind volume (lower left), and the $CO_2$-enriched/ambient-treatment ratios of the first and third of these histories (lower right) for our sour orange tree study, which is currently the longest continuous $CO_2$ enrichment experiment ever to be conducted anywhere in the world.

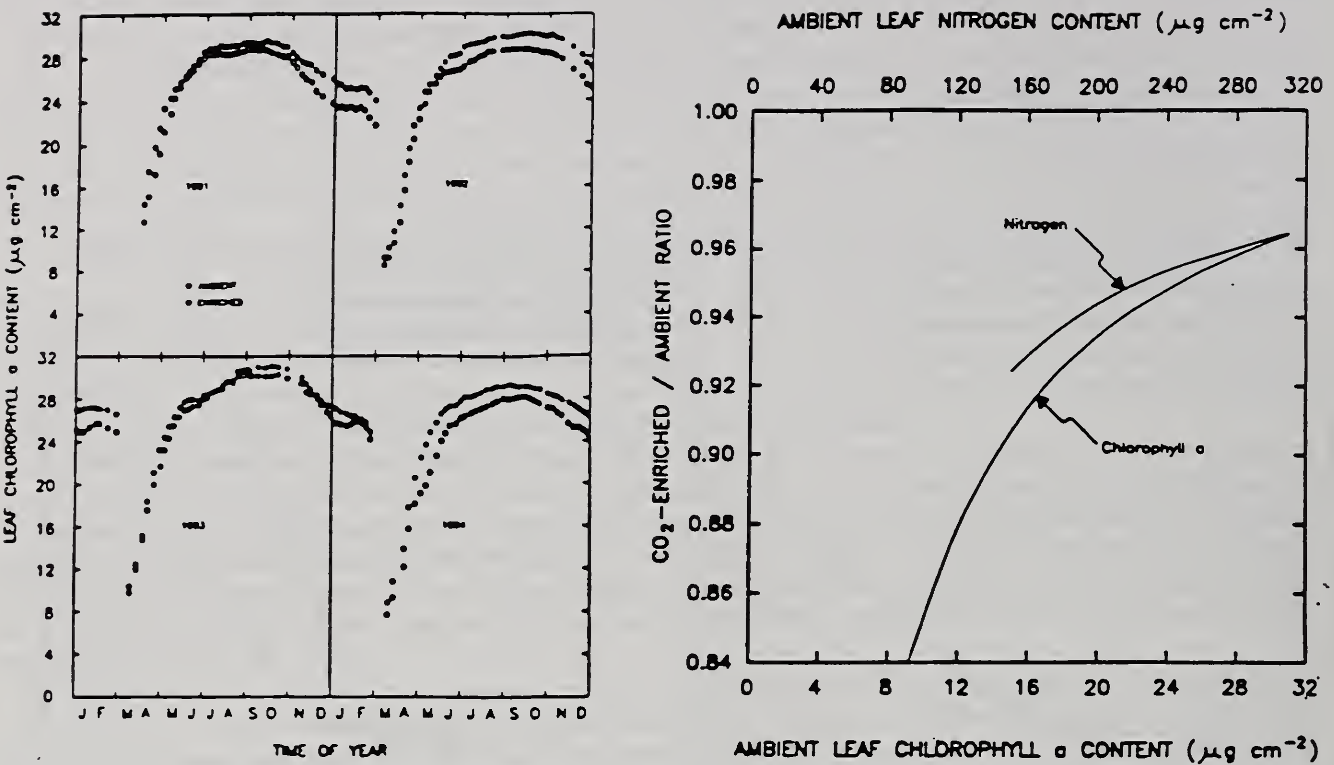


Figure 2. Four years of chlorophyll a measurements of ambient and $CO_2$-enriched sour orange tree foliage (left), and the $CO_2$-enriched/ambient-treatment ratios of leaf chlorophyll a and nitrogen concentrations plotted as functions of ambient-treatment leaf chlorophyll a and nitrogen concentrations (right).

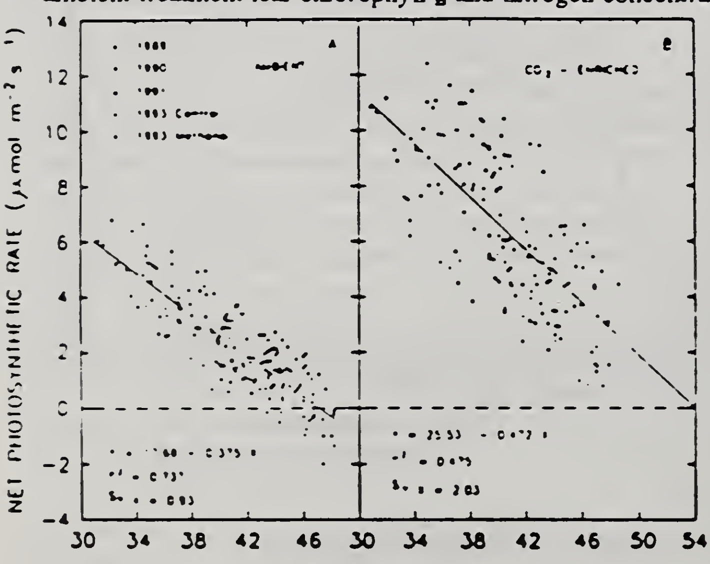


Figure 3. Net photosynthetic rates of ambient and $CO_2$-enriched sour orange tree foliage plotted as functions of leaf temperature.

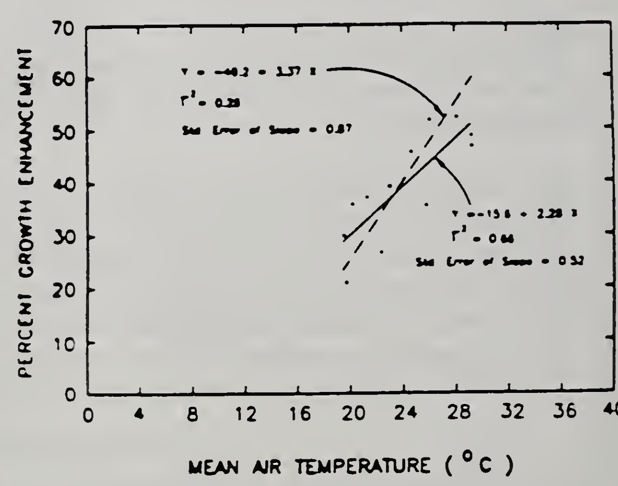


Figure 4. Percent growth enhancement of Agave vilmoriniana provided by a 300 ppm enrichment of the air's $CO_2$ concentration plotted as a function of mean-air temperature. The solid line represents the results of our study, while the dashed line represents the mean result obtained for 16 non-CAM plants by Idso and Idso (Agric. For. Meteorol. 69:153-203).

## SEASONAL DYNAMICS OF PAR ABSORPTION AND CONVERSION EFFICIENCY BY SPRING WHEAT: EFFECTS OF FREE-AIR $CO_2$ ENRICHMENT (FACE) AND WATER STRESS

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**PROBLEM:** Expected changes in global climate and atmospheric carbon dioxide ($CO_2$) concentrations have very major, yet relatively poorly understood, consequences for the productivity of important food and fiber crops. The results of these changes are difficult to assess in traditional experiments using glasshouses or enclosed chambers because the chambers themselves modify many of the environmental parameters (e.g., light, temperature, etc.) That affect plant growth and development. Our quest for more realistic conditions in which to conduct experiments has led us to use a Free Air Carbon dioxide Enrichment (FACE) approach in our cotton and wheat research over the past 6 years. With FACE, experimental findings become more relevant for production agriculture because plants are exposed to natural environmental conditions and function as a complex community, with normal competitive interactions for light, water, and nutrients.

These community-level experiments without interference of light attenuating-chambers also provided an ideal opportunity to test hypotheses regarding the effects of $CO_2$ on the capture of photosynthetically active radiation (PAR) by the whole plant canopy and its subsequent conversion to biomass. However, special techniques were needed to measure the fractional portion of PAR absorbed by the plant canopy (fAPAR). This is because early in the season when plants were less than ~0.25 m in height, conventional line quantum sensors were too large to use effectively. Likewise, late in the season when elevated $CO_2$ and water stress accelerated leaf senescence, an approach was required that was unaffected by the increasing proportion of nonphotosynthesizing canopy elements and provided a realistic assessment of fAPAR by the photosynthetically active component of the canopy.

This report discusses the use of an innovative, non-invasive technique for measuring fAPAR and presents preliminary data on the effects of $CO_2$ and water stress on the seasonal dynamics of fAPAR, and light use efficiency of spring wheat during the 1993-94 FACE experiment.

**APPROACH:** Spring wheat (*Triticum aestivum* L. cv Yecora Rojo) was sown in east-west rows spaced 0.25 m apart at the Maricopa Agricultural Center (MAC) in December 1993. Plants were exposed to enriched (FACE, ~550 $\mu$mol mol$^{-1}$) and ambient (Control, ~370 $\mu$mol mol$^{-1}$) $CO_2$ levels; treatments were replicated four times. $CO_2$ treatment plots were split in half to test the effect of different irrigation regimes on wheat response to $CO_2$. Irrigation of the Wet treatment was based on full-season consumptive use requirements of wheat as determined from estimates of potential evapotranspiration (PET) obtained from the Arizona Meteorological Station at MAC. Plants in the Dry irrigation treatment received only 50% of amounts given to the Wet plots. Irrigation water was delivered to the plants using micro-irrigation (drip) tubing that was spaced 0.51 m apart (parallel to plant rows) and buried at 0.18 to 0.25 m depth.

Approximately 24 wheat plants were sampled from all replicates of each treatment combination at weekly intervals (22 sampling periods). Plant phenology was determined according to both the Zadoks and Haun scales of development. Abovegroundground biomass (crown, stem, green and nongreen leaf, and head components) was measured after oven-drying at 65-70 C. Root biomass was measured from three, 10-cm diameter cores obtained from each replicate at six dates during the season. Green leaf and stem area (GPAI) was measured on a subsample of 12 median-sized plants per subplot using an optical planimeter. The fractional proportion of the canopy that was green (FG) was defined as GPAI divided by the maximum GPAI achieved to date. Typically, FG was one until anthesis then declined to zero at the end of grain filling. The experimental setup and effects of different treatments on plant phenology, growth parameters, and final yield are discussed in more detail by Pinter, et al. (1996).

Canopy reflectance factors were measured one to five times a week using a handheld, Exotech radiometer (Exotech, Inc., Gaithersburg, Maryland) equipped with 15° fov optics. Measurements were made at a 57° solar zenith angle. Red (0.61 to 0.68 $\mu$m) and near-infrared (NIR, 0.79 to 0.89 $\mu$m) reflectance factors were used to compute the Normalized Difference Vegetation Index (NDVI = [(Red-NIR)/(Red + NIR)]. Incident and transmitted light in PAR wavelengths (0.4 to 0.7 $\mu$m) were measured at midday on seven dates during the season using a Ceptometer (Decagon Instruments, Inc., Pullman, Washington). Canopy fAPAR was computed using a light balance equation (Pinter, et al., 1994), and absorbed PAR (APAR) was determined as the product of fAPAR and incident solar PAR.

**FINDINGS:** Traditional methods for measuring and interpreting fAPAR using the Ceptometer were not possible early in the season when wheat was < 0.25 m high. They were also not appropriate to use during the last third of the season (after anthesis, ~DOY 95) when it was obvious that not all PAR energy was being used in photosynthetic processes (fig. 1). To better represent fAPAR over the entire season, we computed a "biologically effective" fAPAR parameter, as the product of measured fAPAR and FG. Effective fAPAR corresponded very well with our intuitive assessment of the canopy and its photosynthetic competence as measured by leaf and whole canopy chamber rates of assimilation (data not shown). When effective fAPAR was plotted versus NDVI (fig. 2), both pre- and post-anthesis wheat data were described adequately by a single relationship having a predictive standard error of $\pm$ 0.05 units. Using the NDVI approach to predict fAPAR permitted its assessment on a season-long basis (fig. 3) and revealed that elevated $CO_2$ conferred a distinct fAPAR advantage over controls during seedling and tillering growth stages (fig. 4). Following anthesis however, senescence progressed more rapidly in the FACE treatments, and their fAPAR declined compared with controls.

Although drought stress in the dry irrigation treatment reduced the seasonal APAR totals by an average of 15%, we were surprised to find no effect of $CO_2$ on end-of-season APAR accumulations (table 1). This was mainly because the FACE plants matured more quickly than controls. When LUE was computed for different intervals in plant development, it revealed intriguing seasonal dynamics of LUE that varied with $CO_2$ treatment and stage of growth (fig. 5). Table 1 contains LUE estimates for each experimental treatment that have been computed in two different ways. The end-of-season LUE was calculated as the final biomass (aboveground and below-ground components) divided by the total accumulated APAR. It showed an overall stimulation of LUE of about 11% under well-watered, nonstressed conditions and about 14% under a more limited irrigation regime. The more conventional, regression-based method for estimating LUE (i.e., the slope of accumulated biomass to accumulated PAR relationship) yielded similar results.

**INTERPRETATION:** Application of multispectral remote sensing techniques for quantifying biophysical plant processes provided data on fAPAR and LUE of wheat throughout the entire growing season. They were particularly useful at the beginning and also at the end of the growing season when more traditional approaches (e.g., use of line quantum sensors) were either physically or biologically inappropriate. In a future high $CO_2$ world, our results show that wheat, like cotton (Pinter et al. 1994), will have an accelerated early-season development of green leaf area. LUE of wheat is expected to increase 12% with a 50% rise in $CO_2$. The within-season dynamics of wheat LUE helped explain a smaller effect of elevated $CO_2$ on biomass and yields than we observed for cotton (Pinter et al. 1996).

**FUTURE PLANS:** Analysis of wheat growth data is continuing. Important questions remain concerning wheat response to $CO_2$ under conditions of limited nitrogen availability. As a result, similar FACE experiments using wheat exposed to two levels of soil nitrogen are planned for the 1995-96 and 1996-97 growing seasons. Measurements of fAPAR and LUE will be rigorously pursued during these experiments.

**COOPERATORS:** A large number of research organizations took an active role in supporting our 1993-94 FACE experiment. See "Progress and plans for the free-air $CO_2$ (FACE) enrichment project" (Kimball et al., in the 1994 USWCL Annual Research Report) for a complete listing of cooperators. We thank the USWCL technical staff for the agronomic data used in this report. The authors also wish to acknowledge the special contributions of Drs. Frank and Gabrielle Wechsung from the Potsdam Institute for Climate Impact Research, Potsdam and Humbolt University, Berlin, Germany, respectively, for providing the root data.

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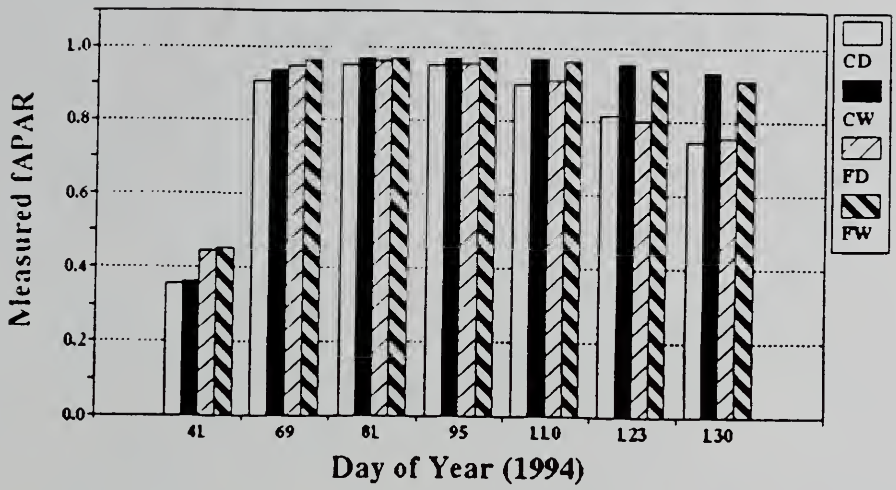


Figure 1. Fraction of photosynthetically active radiation (fAPAR) measured at midday with a Ceptometer during the 1994 FACE experiment with Yecora Rojo spring wheat. Abbreviations: CD, Control Dry; CW, Control Wet; FD, FACE Dry; FW, FACE Wet

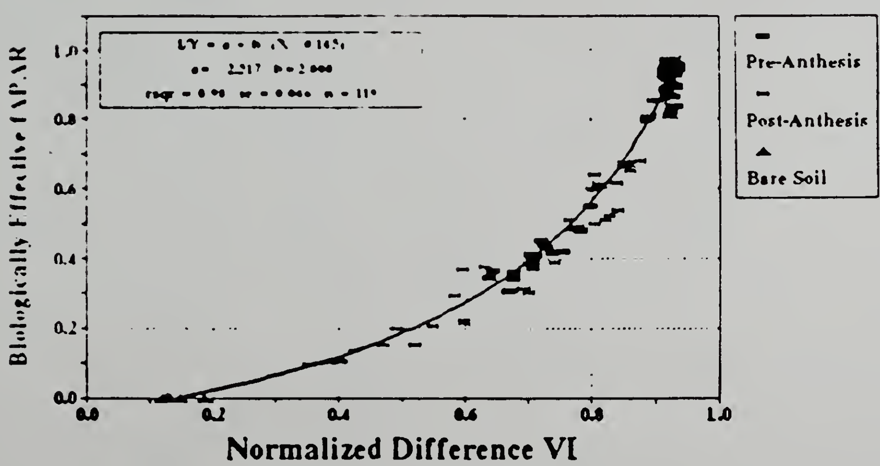


Figure 2. Biologically effective fraction of photosynthetically active radiation (fAPAR) versus the Normalized Difference Vegetation Index (NDVI) measured with the Exotech radiometer

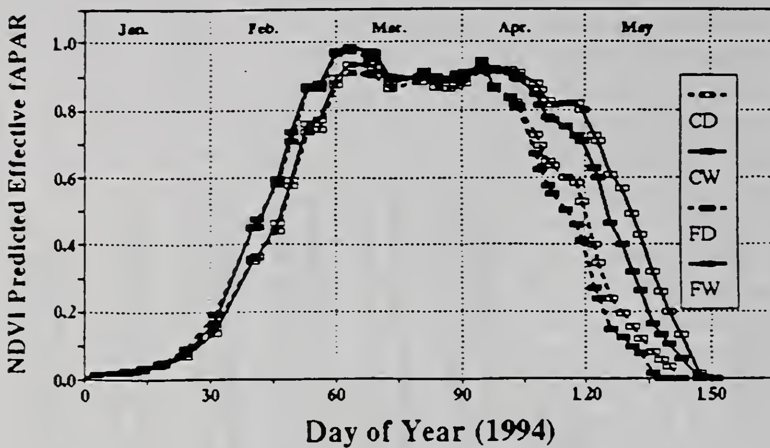


Figure 3. Biologically effective fAPAR predicted as a function of the Normalized Difference Vegetation Index (NDVI) for Yecora Rojo spring wheat in the 1994 FACE experiment. Abbreviations. CD, Control Dry; CW, Control Wet; FD, FACE Dry;

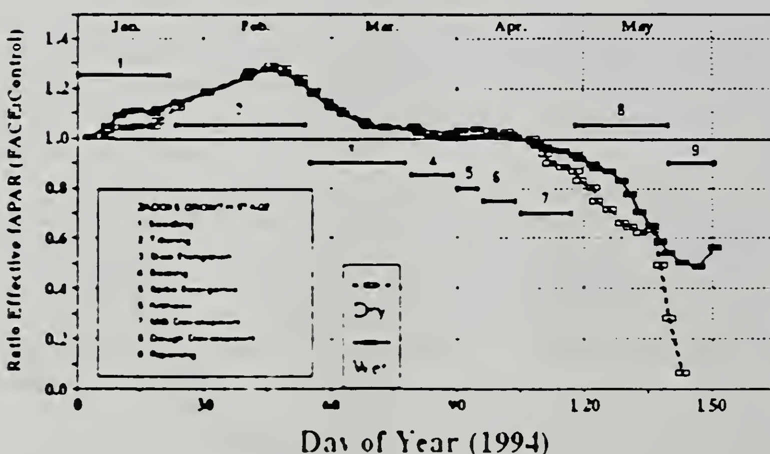


Figure 4. The ratio of FACE to Control biologically effective fAPAR for dry and wet irrigation treatments during the 1994 FACE experiment with spring wheat. Horizontal bars show approximate duration of growth stages.

# EVALUATING PLANT DYNAMICS AS RELATED TO WATER CONSERVATION AND CLIMATE CHANGE USING REMOTE SENSING

# NORMALIZATION OF BIDIRECTIONAL EFFECTS IN VIDEOGRAPHIC IMAGERY

J. Qi and M. S. Moran, Physical Scientists;
P. J. Pinter Jr., Research Biologist; and T.R. Clarke, Physical Scientist

**PROBLEM:** Because of its low cost and flexible data acquisition schedule, videographic imagery has become a practical means to acquire remote sensing data from which to infer crop information for precision farm management. One of the generic problems in using videographic imagery for operational farm management is the nonuniformity in brightness across the imagery due to bidirectional effect. During the imagery acquisition processes, the sun's position and the sensor's viewing angles vary not only across an individual frame, but also from frame-to-frame. Some areas of the resultant images appear darker or brighter than others, depending on the position of the sun and the sensor's viewing angles. The differences in brightness due to bidirectional effect can be as high as 40% and, therefore, videographic imagery must undergo a pre-process procedure to correct the bidirectional effect prior to quantitative analysis. The objective of this study is to develop a practical procedure to normalize the bidirectional effect so that consistent videographic imagery can be obtained for operational farm management.

**APPROACH:** Several bidirectional reflectance distribution function (BRDF) models have been developed in the past decade to predict the consequences of changing sun and viewing angles on observed reflectances (Strahler, 1994; and Cabot et al., 1994). These models potentially can be used to normalize the bidirectional effects (Qi et al., 1995). The empirical model proposed by Shibayama and Wiegand (1985) was used in this study:

$$\frac{\rho(\theta,\varphi)}{\rho(0,0)} = 1.0 + [\beta_0 + \beta_1 \sin(\frac{\varphi}{2}) + \beta_2(\frac{1}{\cos\theta_s})]\sin\theta, \tag{1}$$

where ρ is reflectance, θ is the sensor's viewing angle, θs is the sun zenith angle, and φ is the relative azimuth angle between the viewing azimuth and solar azimuth. The coefficients β1, β2, and β3 are empirical parameters to be determined by an inversion procedure. The practical normalization procedure is outlined in figure 1. Several consecutive frames with 60% overlaps were obtained in such a way that a common feature on ground appears in all frames but at varying locations. Data at these locations were then extracted and used in an inversion procedure to obtain a set of coefficients (β1, β2, β3) used in the BRDF model. These generated coefficients are then used in the model to generate normalization coefficients, which are then applied to all frames to normalize the bidirectional effect. As a demonstration, individual image frames of a bare soil field at the Maricopa Agricultural Center near Phoenix, Arizona, were used. A transect was selected to cross different surface types to study quantitatively the bidirectional effect.

**FINDINGS:** Prior to bidirectional correction, the brightness of videographic imagery varied as much as 24 % in this study because of the difference in the sun's position and sensor's viewing angles (figure 2). When the sun is in the backscattering direction (the sun is in the same direction as the sensing system), the resultant brightness is higher than that when the sun is in the forward direction (the sun is in the opposite direction of the sensing system) for both red and near-infrared channels. When the normalization procedure was applied, the differences in brightness in both channels were greatly reduced as demonstrated in figure 3. The top curves are the brightness values from three different frames over a single field. The upper curves in figure 3a are near-infrared, and the lower ones are red channel values. The curves in figure 3b are the same transect values but after the normalization procedure was applied. The values from the three individual frames were normalized to the same level. The procedure was applied on two individual frames where a soil field appeared twice in the images: one in the forward direction and the other in the backscattering direction. Before the normalization procedure was applied (figure 4a), the discontinuity is apparent. After the bidirectional correction, the discontinuity disappeared (figure 4b). The bidirectional correction procedure normalized the radiometric discontinuities due to sun and viewing angle differences among individual videographic images.

**INTERPRETATION:** The proposed procedure to normalize the bidirectional effect improved the quality of videographic imagery and therefore increased the value of its applications for resources management. The procedure will permit the use of multitemporal videographic imagery in a consistent manner. After normalization of bidirectional effect,

videographic imagery can be used in a quantitative way, and images acquired under different time and sensor geometric configurations can thus be compared directly. This is very beneficial to remote sensing users such as farmers for quantitative and reliable assessment of their crop conditions. It should be pointed out, however, that the normalization procedure requires that multi-frames be obtained in order to yield a reliable set of normalization coefficients. Because the normalization coefficients have to be generated for virtually every pixel, substantial computing time is needed. This limitation can be overcome with availability of faster computers.

**FUTURE PLANS:** The next step is to implement this procedure and make it operationally routine for bidirectional effect corrections. The procedure will be implemented on both personal computers and workstations.

**COOPERATORS:** C. U. M. Neale, S. Sundararaman, and R. Ahmed, Department of Biological and Irrigation Engineering, Utah State University, Logan, Utah.

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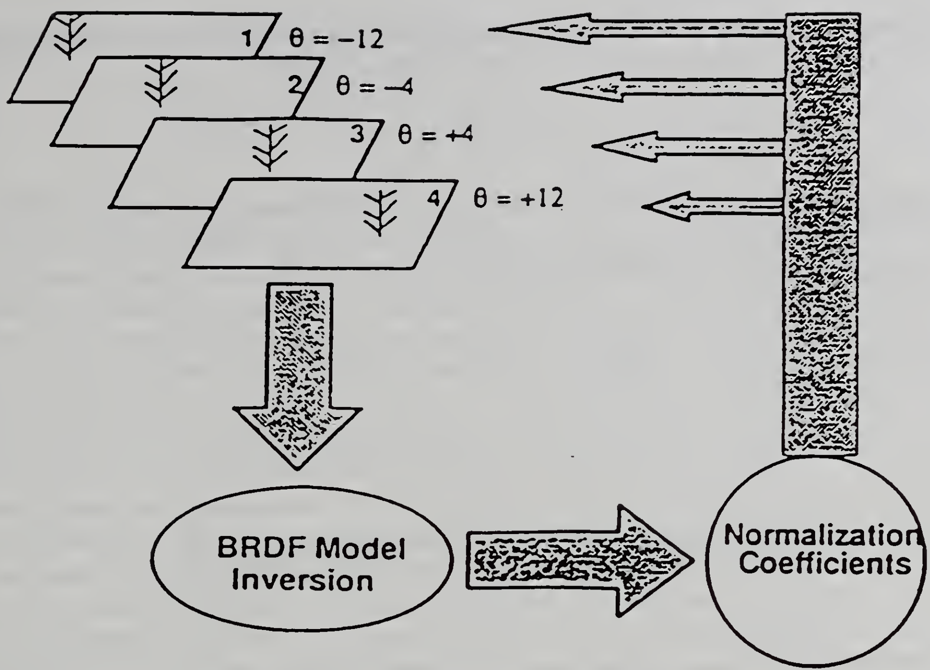


Figure 1. Schematic view of the procedures for bidirectional effect corrections on videographic imagery.

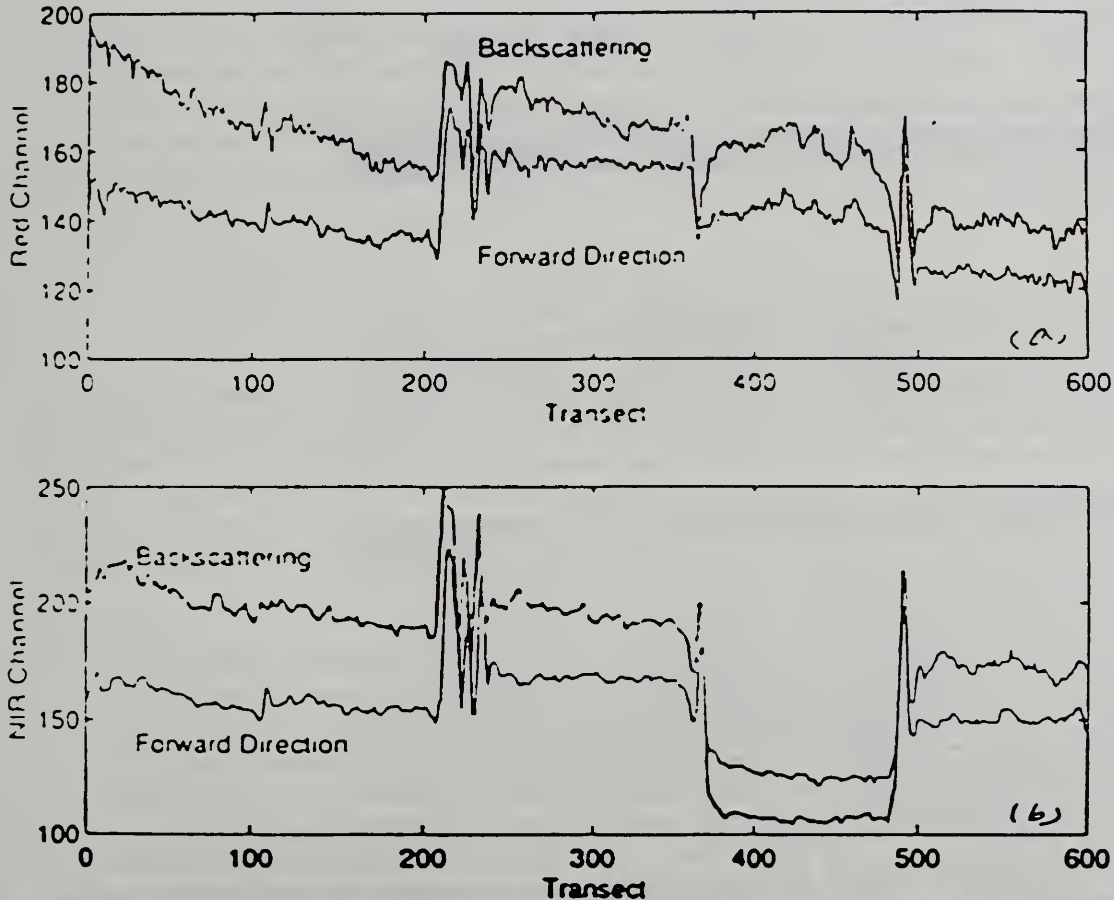


Figure 2. Radiometric discontinuity along the center of a field. Data in the upper curves were grabbed from a frame that corresponds to backscattering, while lower curves are from forward direction.

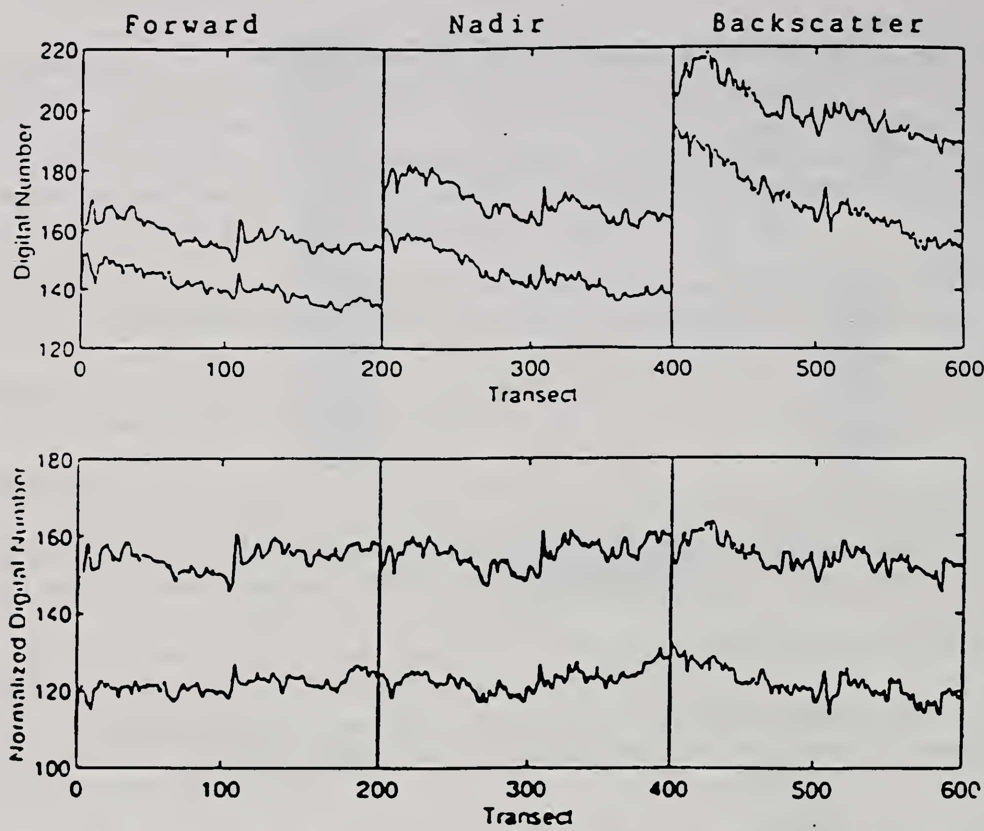


Figure 3. Comparison between results of before and after normalization procedure applications.

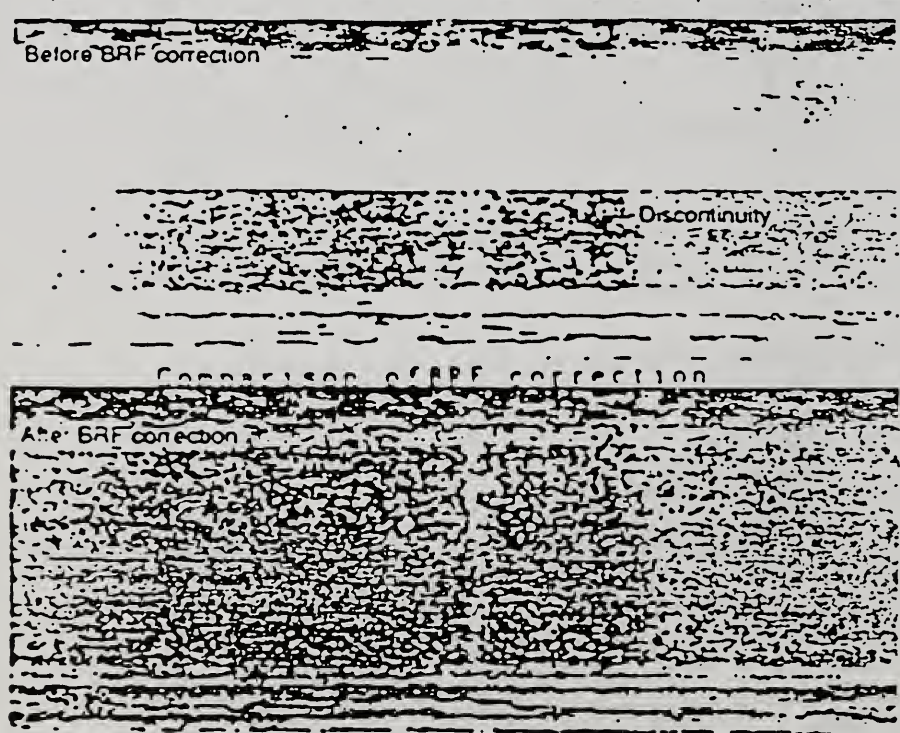


**Figure 4. Demonstration of radiometric discontinuity at joining boundaries when mosaicking two individual frames before and after bidirectional corrections.**

**BIDIRECTIONAL AND ATMOSPHERIC CONSIDERATION IN COMPOSITING MULTITEMPORAL AND MULTIDIRECTIONAL REMOTE SENSING DATA**

J. Qi and M. S. Moran, Physical Scientists

**PROBLEM:** With increasing demand for frequent observations of the planet Earth from space for global change studies, about a dozen orbiting satellites have been operational, and more advanced satellites have been scheduled to launch in the near future. Examples are the advanced, very high resolution radiometer (AVHRR) on the National Oceanic and Atmospheric Administration (NOAA) satellite series and the proposed moderate-resolution imaging spectrometer (MODIS) to be on board the Earth Observing System (EOS) platforms. These sensors have the ability to sense the entire earth on a daily basis because of their large field of view (FOV). Data acquired with these operational satellites are usually processed using a compositing technique to remove or reduce the effects of clouds and poor atmospheric conditions (Qi et al., 1995). The current compositing technique selects the data point, from a predefined window period, that has the maximum value of the normalized difference vegetation index (NDVI). Because of the dependency of NDVI on external factors such as atmospheric condition and surface bidirectional properties, two major issues have been raised recently: 1) should the NDVI be computed prior to or after the atmospheric correction, and 2) what is the consequence of bidirectional effects on the composited results? The objective of this study is first to investigate the consequences of atmospheric correction and second to incorporate a bidirectional reflectance distribution function (BRDF) model into the current compositing technique to normalize sun and viewing angle influences on the composited remote sensing observations. The focus will be on the development of a compositing technique that will optimize atmospheric correction procedures and incorporate BRDF models for bidirectional correction.

**APPROACH:** Multitemporal remote sensing images obtained with the Advanced Very High Resolution Radiometer (AVHRR) were obtained over four different vegetation types (Millet, Tiger bush, Fallow, and Degraded fallow) over the Hapex Sahel Experiment sites near Niamey, Niger, in 1992. The maximum value compositing (MVC) technique was applied on this data set both before and after atmospheric corrections to examine the consequences of atmospheric correction. Then an empirical BRDF model proposed by Shibayama and Wiegand (1985) was applied to normalize the bidirectional effects:

$$\frac{\rho(\theta,\varphi)}{\rho(0,0)} = 1.0 + [\beta_0 + \beta_1 \sin(\frac{\varphi}{2}) + \beta_2(\frac{1}{\cos\theta_s})]\sin\theta, \qquad (1)$$

where $\rho$ is reflectance, $\theta$ is the sensor's viewing angle, $\theta_s$ is the sun zenith angle, and $\varphi$ is the relative azimuth angle between the viewing azimuth and solar azimuth. The coefficients $\beta 1$, $\beta 2$, and $\beta 3$ are empirical parameters to be determined by an inversion procedure. The normalized data were then composited with the MVC technique. The resultant composited data of all four vegetation types were then compared to examine the consequences of bidirectional corrections. Finally, a sensitivity analysis was conducted to examine the advantages and disadvantages of incorporating a BRDF model into the current compositing technique.

**FINDINGS:**

1. The bidirectional effect is significant and must be considered in compositing procedures. In figure 1, the raw AVHRR data in channels 1 and 2 are depicted as the dotted lines for the four vegetation types. The solid lines with stars (*) and circles (o) are the reflectances after the MVC compositing technique was applied, whereas the solid lines with crosses (+) were the absolute view angles corresponding to the selected data points. The cloud-contaminated pixels could easily be seen because of their exceptionally high values in channels 1 and channel 2 for all vegetation types in this study. The remaining high frequency variations of the reflectances were due partly to the atmospheric variations in such components as water vapor content, aerosols, and ozone concentrations; and partly to the surface bidirectional effect caused by the differences in view angles and solar position. It is apparent that the data would be useless unless clouds are removed and atmospheric and bidirectional effects are reduced. The composited data appeared to follow exactly the pattern of the viewing angles.
2. The sequences of atmospheric correction appeared to be less important, but compositing prior to atmospheric correction seemed to result in a less noisy temporal profile. The comparison of the composited results before and

after atmospheric corrections are depicted in figure 2; where the top profiles are the raw data in channels 1 and 2, whereas lines with star "*" and circle "o" symbols are the composited results. Since the absolute values of these temporal profiles are not the major concern in this study, the data were plotted with different additive scaling factors to separate them for a better graphic view. The temporal profiles showed no significant difference before and after atmospheric corrections.

3. Incorporation of a simple BRDF model significantly reduced the noise due to sun and view angle effects. To illustrate the improvement in the composited data by using the BRDF model corrections, data sets composited before and after bidirectional corrections were plotted (different constants were added to have a better graphic view for comparison) against each other in figure 3. Variations in both channels 1 and 2 found before bidirectional corrections seemed to disappear from the data after bidirectional corrections, indicating that the simple BRDF model could be used in the normalization of bidirectional effect on AVHRR data.
4. The sensitivity analysis showed that by incorporating a BRDF model in the MVC compositing, not only the bidirectional effects were reduced, but the composited NDVI results were more correlated to the vegetation amount (table 1) as indicated by the correlation coefficients between NDVI and leaf area index values.

INTERPRETATION: The proposed incorporation of both atmospheric and bidirectional correction procedures improved the quality of composited AVHRR data. The atmospheric correction and bidirectional corrections reduced view angle effects as well as the atmospheric effect, resulting in smoother temporal profiles for all sites in this study. The incorporation of these two correction procedures in compositing also increased the sensitivity of the NDVI to vegetation changes. It is consequently beneficial to perform both atmospheric and bidirectional corrections prior to the compositing process when dealing with multitemporal AVHRR data. The incorporation of bidirectional correction procedures into the MVC technique will improve the data quality for global change and resources management studies. The sequence of processing AVHRR data ought to proceed, based on this study, in the following way: 1) make atmospheric corrections; 2) make bidirectional corrections; 3) apply the MVC compositing technique to select the best data points. In case bidirectional correction is not available, apply compositing procedure first, and then perform the atmospheric corrections on the composited results. This would not only result in a smoother temporal profile, but also reduce the computing time on atmospheric correction because the atmospheric correction will be applied only to the composited data. Operational implementation of bidirectional correction should be feasible, such as using a simple BRDF model in this study.

FUTURE PLANS: The next step is to incorporate the bidirectional correction and atmospheric correction procedures in the current compositing technique. These procedures will be implemented in an operational way to be ready to apply on multitemporal remote sensing images obtained with different satellite sensing systems.

COOPERATORS: Y. Kerr, CESBIO, CNES, France; and E. Vermonte, GSFC, NASA.

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Table 1. Correlation coefficients (CC)of reflectances and NDVI with noise and leaf area index (LAI) for all sites of different compositing procedures. The goodness ranking: 1=Best, 4=worst.

| BRF Corrections | ATM. Corrections | CC of Reflectance with View Angles | | | | | Goodness Ranking |
|---|---|---|---|---|---|---|---|
| | | Fallow | Millet | D Fallow | T Bush | Total | |
| NO | NO | 0.452 | 0.512 | 0.405 | 0.580 | 0.491 | 3 |
| NO | YES | 0.698 | 0.528 | 0.460 | 0.546 | 0.561 | 4 |
| YES | NO | 0.280 | 0.379 | 0.443 | 0.394 | 0.369 | 2 |
| *YES* | *YES* | *0.111* | *0.167* | *-0.005* | *0.179* | *0.092* | *1* |
| | | CC of NDVI with LAI | | | | | |
| NO | NO | N/A | 0.741 | 0.753 | N/A | 0.746 | 3 |
| NO | YES | N/A | 0.624 | 0.523 | N/A | 0.578 | 4 |
| YES | NO | N/A | 0.785 | 0.805 | N/A | 0.794 | 2 |
| *YES* | *YES* | *N/A* | *0.903* | *0.990* | *N/A* | *0.901* | *1* |

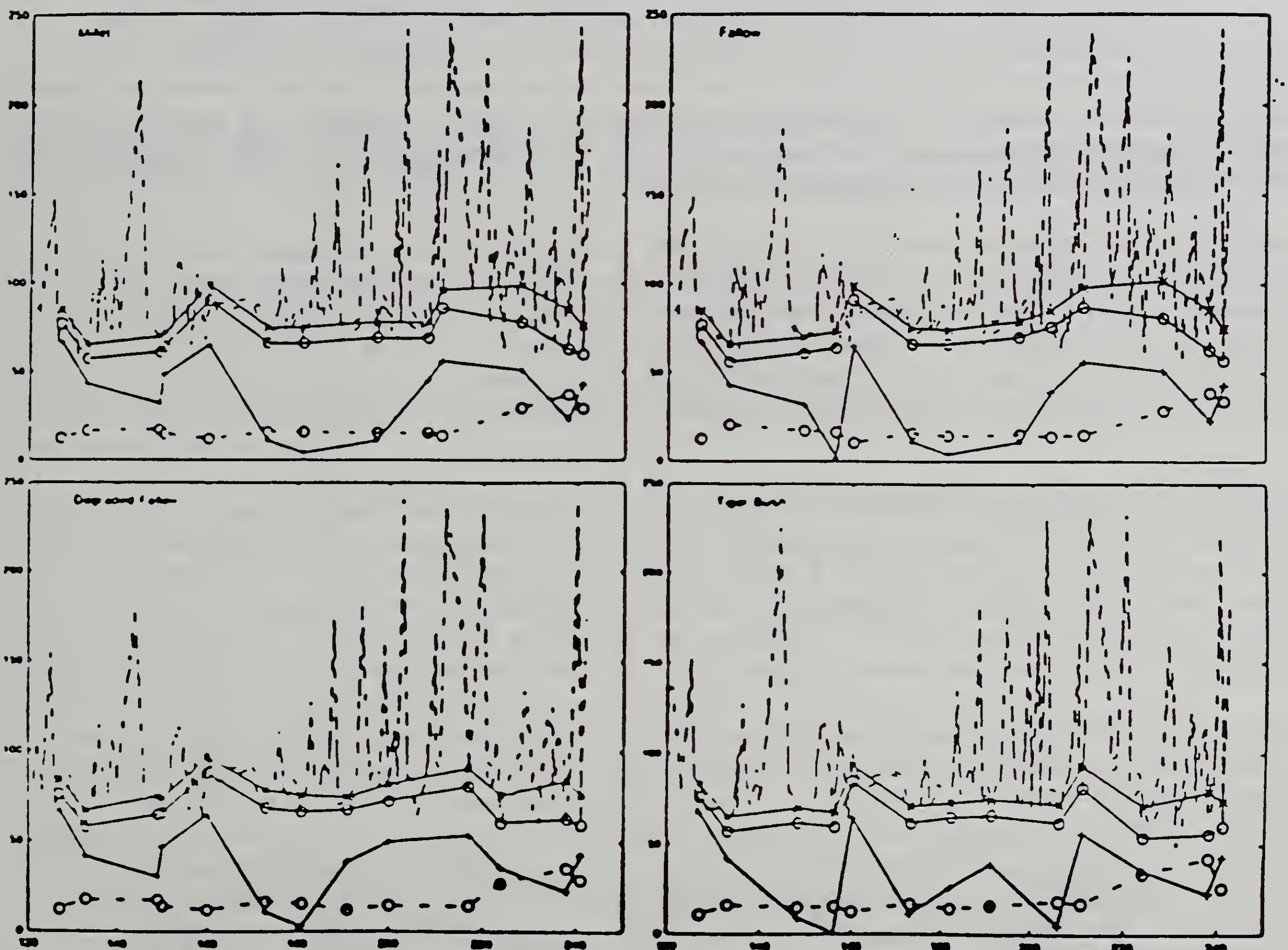

Figure 1. Temporal profiles of reflectances before atmospheric corrections and their composited results for the four selected sites. The noise dotted lines are the raw profiles while the solid lines with stars "*" are near-infrared and those with circles are red reflectances. The solid lines with crosses "+" are the view angles, and the dotted lines with circles are the NDVI profiles. These variables were scaled to different levels for a better display.

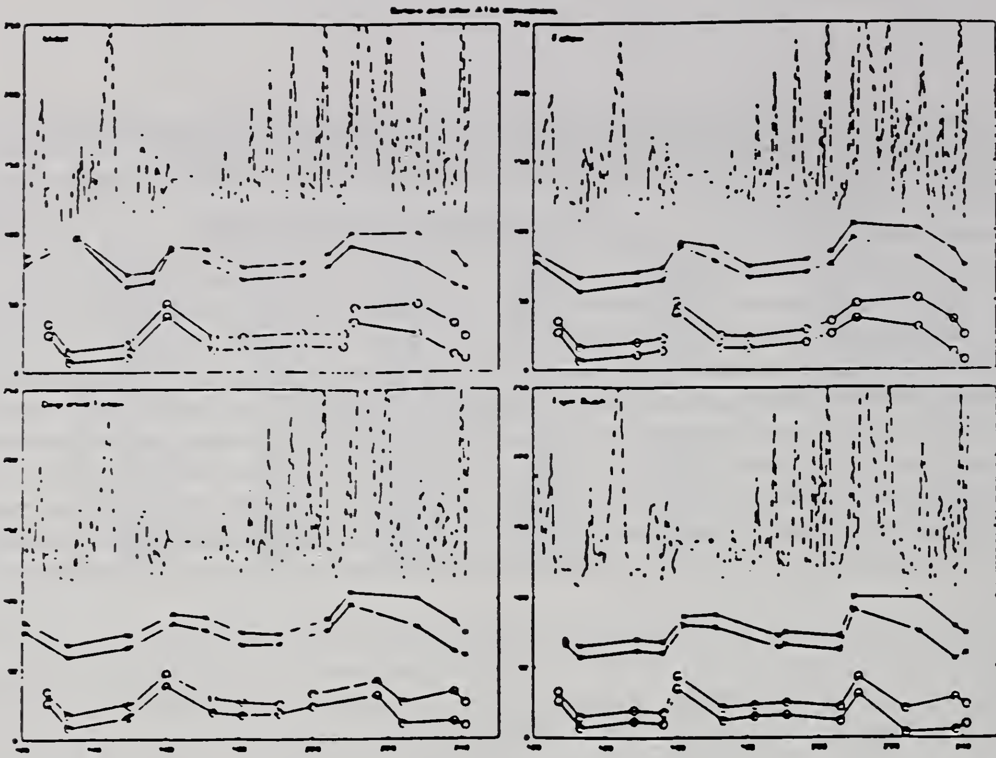

Figure 2. Comparison between composited results before and after atmospheric corrections. The solid lines with stars "*" are the profiles after atmospheric corrections (the upper one is NIR and the lower one is red), whereas those with circles "o" are the profiles before the atmospheric corrections.

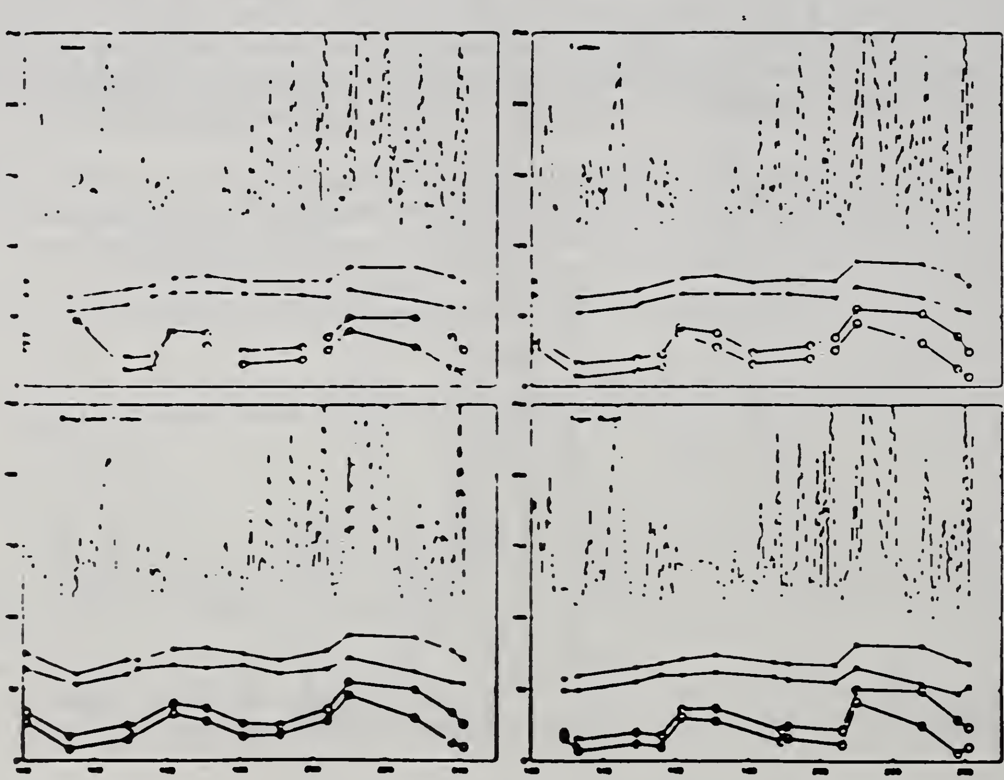

Figure 3. Comparison between composited results before and after bidirectional corrections. The solid lines with stars "*" are the profiles after atmospheric corrections (the upper one is NIR and the lower one is red), whereas those with circles "o" are the profiles before the atmospheric corrections.

# COMBINING THE PENMAN-MONTEITH EQUATION WITH LANDSAT TM DATA TO MAP REGIONAL EVAPORATION RATES

M.S. Moran, Physical Scientist

**PROBLEM:** Current interest in the prediction of drought, forest fires, and regional changes in climate has resulted in a related interest in making maps of vegetation health. It is commonly accepted that vegetation health is directly related to plant transpiration rates, where plant transpiration rate generally decreases with lack of water, insect infestation, disease, or extreme weather conditions. The Penman-Monteith equation is useful for computing evaporation rates of uniform surfaces, such as evaporation from bare soil or transpiration from dense vegetation. This equation becomes less useful for evaluation of evapotranspiration (ET) rates at the regional scale, where surfaces are generally characterized by a patchy combination of vegetation and soil. This is particularly true in the arid and semiarid regions of the world.

**APPROACH:** The approach proposed here was an attempt to use remotely-sensed measurements of surface reflectance and temperature to allow application of the Penman-Monteith theory to partially vegetated fields without a prior knowledge of the percent vegetation cover and canopy resistance (Moran et al., 1995). Basically, the Penman-Monteith equation was combined with the energy balance equation to estimate the surface temperature ($T_s$) associated with four states: surfaces characterized by full-cover vegetation and bare soil with evaporation rates at potential ($ET_p$) and zero (Moran et al., 1994). Then, linear interpolations between $T_s$-$T_a$ values computed for full-cover and bare soil conditions were used to produce a vegetation index/temperature (VIT) trapezoid (figure 1). A soil-adjusted vegetation index (SAVI) was computed from a ratio of red and NIR reflectances and linearly correlated with vegetation cover, where SAVI=0.0 was associated with bare soil conditions and SAVI=0.7 was associated with full-cover vegetation. An index (termed the Water Deficit Index: WDI) was computed, where WDI = $ET/ET_p$ based on the ratio of AC/AB in figure 1. Thus, plant health could be rated from good (WDI=0) to poor (WDI=1) based on measurements of $T_s$-$T_a$ and SAVI for each resolution cell.

The approach was first tested using ground-based measurements of surface reflectance and temperature at a rangeland site. Then, the approach was tested based on a set of four Landsat Thematic Mapper (TM) images acquired in southeast Arizona during 1992. Maps of surface air temperature and wind speed were combined with maps of surface temperature and spectral vegetation index to produce regional estimates of evaporation rates for the grassland biome. At the local scale, modeled evaporation rates were compared with ground-based measurements at one site; at the regional scale, the modeled evaporation rates for the entire grassland biome were validated with knowledge of recent rainfall events and on-site meteorological conditions.

**FINDINGS:** For a grassland site in the USDA-ARS Walnut Gulch Experimental Watershed (WGEW) in southeastern Arizona, we computed the VIT trapezoid and determined the WDI based on ground-based measurements of $T_s$ and SAVI on each date. With a computation of potential $ET_p$ for each date, we were able to retrieve instantaneous actual ET (W $m^{-2}$) from the WDI and compare that with the values of ET measured on-site (Kustas et al., 1994). The "modeled" values based on the VIT trapezoid compared well with the measured values (RMSE = 29 W $m^{-2}$ over a range of ET values from 200-450 W $m^{-2}$) (figure 2). However, there was a trend for the modeled ET to overestimate the measured values in most cases (Mean Absolute Difference (MAD) = 45 W $m^{-2}$).

In order to compute WDI on a regional basis, maps of $T_a$, wind speed (U), vapor pressure deficit (VPD), and incoming solar radiation were derived from measurements made at 13 meteorological sites within a 100x100-km area in southeastern Arizona. These maps of meteorological conditions were combined with four associated Landsat TM images of surface reflectance and temperature for a large grassland biome within the TM image. The rainfall and soil moisture conditions associated with the four dates are as follows:

| Day-of-Year 1992 | Last Rain | Amount of Rain in Last 30 Days | Soil Moisture |
|---|---|---|---|
| 162 10 June | 30 May, 0.5 mm | 32 mm | 2 % |
| 178 26 June | 30 May, 0.5 mm | 2 mm | 2 % |
| 274 30 Sept. | 20 Sept., 0.7 mm | 7 mm (Rain in Aug: 117mm) | 3 % |
| 306 2 Nov. | 28 Oct., 11 mm | 14 mm | NA |

The WDI was computed for each pixel within the subset of the Landsat TM scenes covering the grassland biome. The VIT trapezoids encompassed the majority of the data on each date (figure 3). It is notable that data scatter on day-of-year

(DOY) 178 (the driest date) did not approach the theoretical "cool" edge of the trapezoid. On the other three dates, the scatter touched and sometimes exceeded the cool edge. On DOY 162 (the wettest date), the highest density of points was located in the middle of the trapezoid, unlike the other days where the highest density of points was located close to the "warm edge." There was a tendency for the TM data to exceed the confines of the warm edge of the VIT trapezoid (e.g., DOYs 178, 274 and 306). It appeared that either the VIT trapezoid method tended to underestimate the temperature of the warm edge, or the surface temperature data from the Landsat TM images were overestimated.

**INTERPRETATION:** It is possible that errors in the computation of the warm edge (figure 3) could be due to errors in the calculation of net radiation ($R_n$), soil heat flux (G) or aerodynamic resistance ($r_a$). However, since the method worked well at the local scale (figure 2), it appears that these inputs were reasonable. Another source of error could be the calibration and atmospheric correction of the remotely-sensed data, causing an overestimation of the surface temperature. In fact, Washburne (1994) found that the satellite temperatures computed from these 1992 images were consistently warmer (by up to 3°C) than aircraft and ground-based measurements. For the conditions at WGEW, an error of 1°C in surface temperature could result in an error of 50 W m$^{-2}$ in the estimation of ET. Thus, this 3°C overestimation of surface temperature would account for the majority of the pixels for which ET was underestimated.

Based on analysis at the local and regional scale, it appears that this approach is reasonable and has some potential for mapping evaporation rates of heterogeneous landscapes. Assuming that the vegetation type is known (using a biome map or other information), the inputs required were only:

1. spatially-distributed meteorological measurements of $T_a$, U, $R_n$, G, and VPD,
2. remotely sensed measurements of $T_s$ and SAVI, and
3. estimates of surface roughness ($z_o$) and displacement ($d_o$) heights.

**FUTURE PLANS:** The sources of error for application of this approach at the regional scale are numerous and need to be analyzed for impact on the results. A sensitivity analysis will be performed to investigate the effects of topography on surface reflectance and temperature measurements, the error associated with applying an atmospheric correction computed at one altitude to an image composed of multiple altitudes, and the sensitivity of the procedure to differences in surface emissivity. The error associated with variations in emissivity could be reduced by estimating the surface emissivity from measurements of surface reflectance, as suggested by Van de Griend and Owe (1993).

One idea that deserves further consideration is the use of data from a large bare soil site within the image as a baseline from which to understand the scattergrams of the other biomes. This approach would be applicable only to certain scenes but may hold some promise to minimize the meteorological measurements required by the technique.

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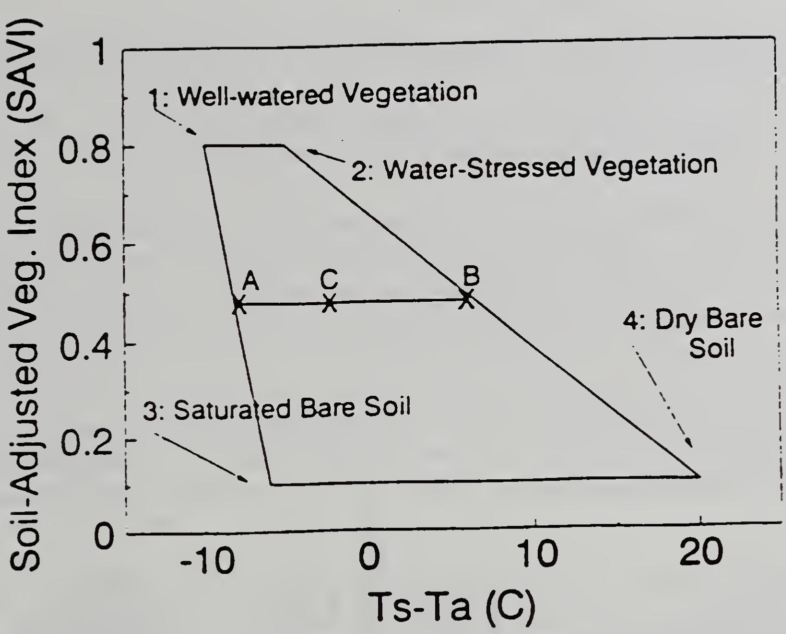


Figure 1. The trapezoidal shape of the Vegetation Index/Temperature (VIT) relation derived from the Penman-Monteith equation. The Water Deficit Index (WDI) is equal to the ratio of AC/AB and ranges from 0 for a well-water crop to 1 for a crop under extreme water stress.

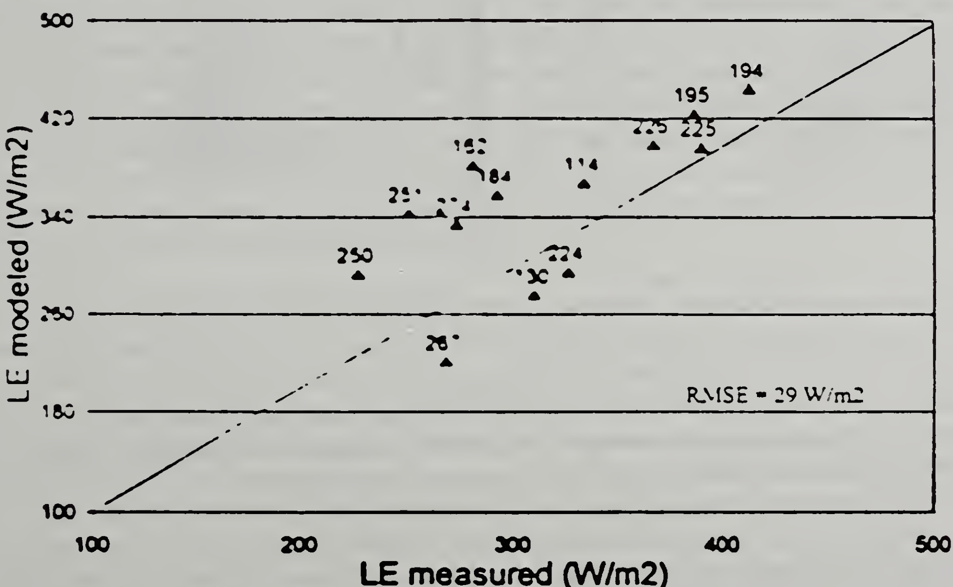


Figure 2. Comparison of instantaneous actual evapotranspiration (W m$^{-2}$) derived from the WDI model with measurements of evapotranspiration measured on-site. Numbers above symbols represent the day-of-year 1992. Note that the terms ET are used interchangeably with the terms LE, where the former are in units of mm hr$^{-1}$ or mm day$^{-1}$, and the latter are expressed in energy units (W m$^{-2}$ or MJ m$^{-2}$ day$^{-1}$).

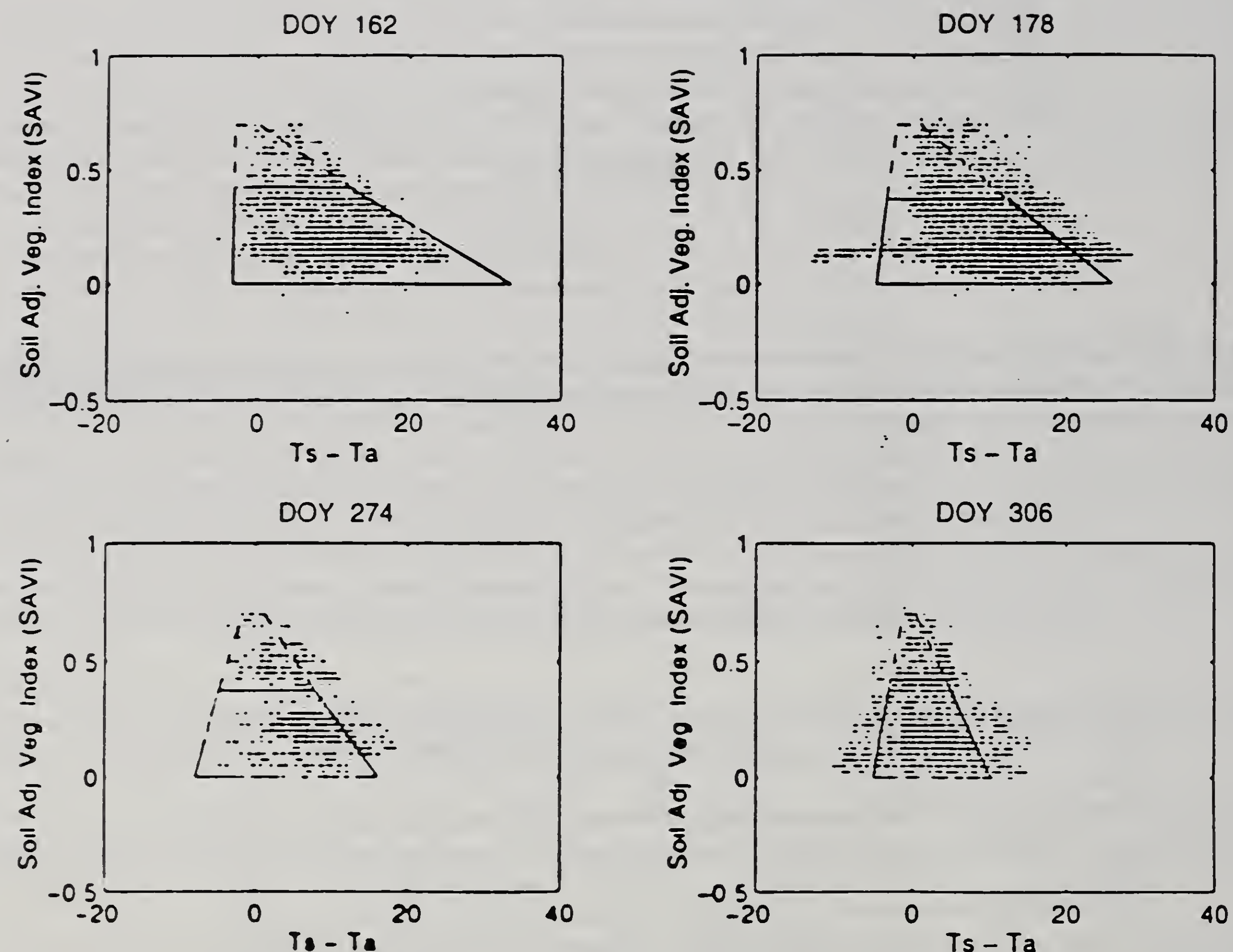


Figure 3. Scattergram of $(T_s-T_a)$ by SAVI from the four Landsat TM scenes for the grassland biome. The VIT trapezoid was computed for each overpass date based on the average $T_a$ and U values derived from the interpolated $T_a$ and U maps and values of VPD, $R_s$ and G measured on-site.

## GEOMETRIC RECTIFICATION OF MULTITEMPORAL, MULTISPECTRAL VIDEO IMAGERY

T.A. Mitchell, Engineering Technician;
J. Qi, T.R. Clarke, and M.S. Moran, Physical Scientists

**PROBLEM:** Images acquired with airborne video cameras can be very useful for farm management. Crop information, including water stress, can be extracted from multitemporal and multispectral images. The accuracy of information extracted from these images depends on the optical and geometric quality of the images. Airborne videographic images are characterized by distortions that occur because of unique camera optics and the attributes of the airborne platform. The interlacing of two video "fields" to produce each video frame results in a fractional, horizontal line shift of odd and even lines within the frame that blurs feature edges (fig. 1). The multi-camera system results in a misregistration of bands that varies throughout the flight because of varying aircraft elevation, motion, and shudder. Thus, traditional methods for registering multitemporal images (developed for satellite-based systems) are not satisfactory for application to airborne video imagery. In this study, new techniques were developed to register multitemporal and multispectral video images more precisely (Mitchell et al., 1995).

**APPROACH:** A total of fourteen sets of multispectral images were acquired over The University of Arizona Maricopa Agricultural Center (MAC) in Maricopa, Arizona, during the Multispectral Airborne Demonstration at the Maricopa Agricultural Center (MADMAC) experiment in 1994. These images were recorded using a multispectral airborne video system and were digitized post-flight. Images collected for this experiment were recorded at 550 nm (green), 650 nm (red), 850 nm (near infrared), and 8-12 $\mu m$ (thermal) wavelengths with four separate cameras.

Automated analysis software was developed for line-by-line analysis of each video frame to determine the fractional, horizontal line shift. This was accomplished by making comparisons between the slope of feature edges for even lines and the relative line shift of odd lines from this slope (fig. 2). Analysis of the statistical mean and standard deviation for these net shifts were used to identify any shift anomalies, which were discarded from the calculation of the shift for that line. This was repeated for all sets of odd and even lines in the image, and using the same statistical mean and standard deviation calculations for the individual lines, outlying shifts were discarded and replaced with interpolated values. This algorithm provided an automated means for correcting continuously-changing, fractional line shifts that appear in videographic imagery.

Because separate cameras were used for each wavelength, geometric band registration was required. Band-to-band misregistration, caused by small changes in aircraft motion, is commonly accomplished using automated image correlation techniques, where the alignment is determined by the location of the highest image correlation. This worked well for the red/green band registration at MAC because the images were positively correlated for all targets. However, the NIR band was both positively and negatively correlated with the red or green band, depending upon the feature. When an attempt was made to correlate the NIR with the green or red images, the positive and negative correlations for the different features begin to add destructively, causing an erroneous shift. This problem was resolved by treating both images with a high pass filter to identify changes related to feature boundaries and then taking the absolute value of this change, thereby providing only positive correlations between bands.

**FINDINGS:** In images of the MAC farm, the interline shifting was quite apparent when inspected at the pixel level (fig. 1). Comparison of this shift with the 2-m resolution of the video imagery revealed an overlap of 50% between the odd and even lines, corresponding to the average vertical line shift in the image (fig. 2). This indicated that 25% of the data was sampled twice, and another 25% was not sampled at all. Horizontal line shifting, forming zig-zag patterns at feature boundaries, was more noticeable than vertical line shifting, and therefore more attention was given to its correction. By making use of feature edges found in the images of geometric landscapes such as farmland, analysis of the horizontal and vertical shift of the aircraft was determined by comparing the slope lines and shifts. Calculation of the statistical mean of these slope-adjusted horizontal shifts, with the exclusion of outlier values, contributed to a better assessment of fractional shift values that more accurately represent the interline horizontal shifts in the video frames.

Analysis of the MAC images revealed that the interline shift varied sporadically within a single frame, making constant shift corrections insufficient (fig. 3). Proper rectification involved individual corrections to be made on a line-by-line basis. Further analysis revealed that the average shift was typically less than a single pixel, and in the case of highly geometric landscapes such as farmland, fractional shifts of less than one pixel were quite noticeable at field borders. By correcting for these fractional shifts with linear interpolation resampling, pixel values were extracted that more closely

represented the true ground region (fig. 4). Inspection of feature boundaries revealed the improved line-to-line registration accomplished by this horizontal shift correction (fig. 5).

A typical frame was found to contain several different features like fields of loose bare soil, packed dirt roads, water bodies, and vegetation (fig. 6), which can all correlate differently between bands (fig. 7). Registration of the MAC images using standard image correlation worked well between the red and green bands but proved unreliable for the NIR registration. The reason for difficulty with the NIR images was found to be the existence of both positive and negative correlations in the feature scenes. Inspection of the band profiles for these regions revealed that the red and green bands were positively correlated with one another for all features, while this was not true for the NIR band (fig. 7). As the shifts between the NIR band and the others were calculated, the positive and negative correlations for the different features added destructively, causing error in estimating the true shift.

To resolve this, a special high pass filter was derived for a 7x7 pixel kernel. The overall kernel dimensions and high-pass filter weighting function were determined empirically to work well with the video imagery of MAC. This filter gave extremely effective results for the green and red image registration, but it produced the same failure as before with the NIR band. This was again due to the existence of positive and negative correlations, which were not removed during high pass filtering. Inspection of the filtered band profiles revealed that the same correlation relationships among the three bands were even more pronounced than for the original data (fig. 8).

The final solution to this problem was found to exist in the detection of feature boundaries that could be represented by positive increases regardless of the direction of change in the image. Taking the absolute value of this change enhanced each boundary as a positive increase and thereby provided for only positive correlations between bands. Visual inspection of known ground points in the MAC images revealed that the application of this algorithm resulted in exceptional band registrations for all bands, including the NIR. The success of this absolute-value, high-pass filter can be attributed to its generation of strictly positive correlations at feature boundaries (fig. 9).

By tracking the statistical mean and standard deviation of the band registration shifts, the accuracy and speed of this software were greatly increased over multiple frames. Use of this algorithm on the MAC images resulted in a failure rate less than 2% and a registration time less than 15 minutes per 80 sets of individual three-band images on a Silicon Graphics Indy workstation.

INTERPRETATION: Interline shifting in airborne video frames was alleviated in geometrically-featured imagery using slope and shift correlations. Fractional shifts were detected on a line-by-line basis, and using statistical analysis, an accurate correction for this interline shifting was accomplished. Correlation methods of determining horizontal and vertical alignment between bands can often fail because of the existence of both positive and negative correlations, which add destructively and hide the true band shifts. While high-pass filtering did not alleviate this problem, an absolute-value, high-pass filter produced only positive correlations and succeeded in proper band registration. Applications of interline shift and band registration corrections allowed for a greater accuracy in geometric rectification, thereby producing greater confidence in multitemporal analysis of multispectral videographic imagery.

FUTURE PLANS: Future plans are focused on the retrieval of pertinent crop and soil information from the corrected, multispectral MADMAC images. We are currently working on assimilation of MADMAC remotely-sensed images into a physically-based simulation model to provide accurate, *daily* soil and crop information. This work will be directly related to irrigation scheduling at MAC.

COOPERATORS: C.M.U. Neale, Dept. of Biol. and Irrig. Engineering, Utah State University, Logan, UT; R.A. Schowengerdt, Elec. and Comp. Eng. Dept., Univ. of Ariz., Tucson.

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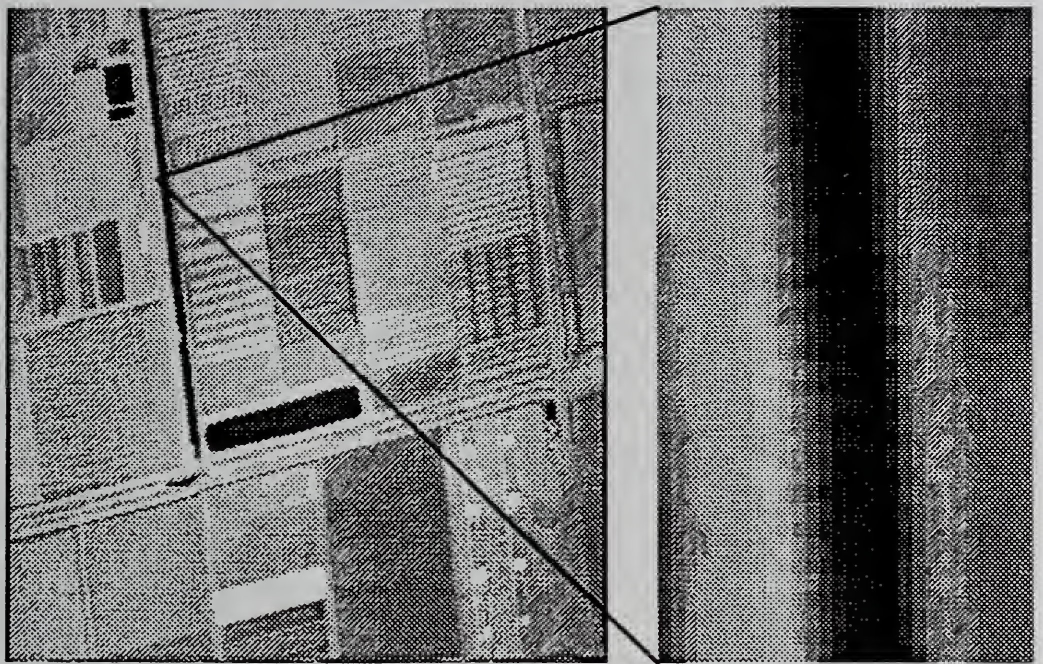

Figure 1. Image of MAC with line shift problems at feature edges.

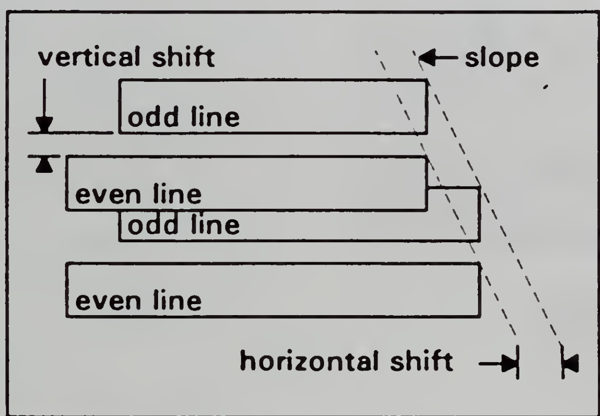


Figure 2 Characteristics of line shift.

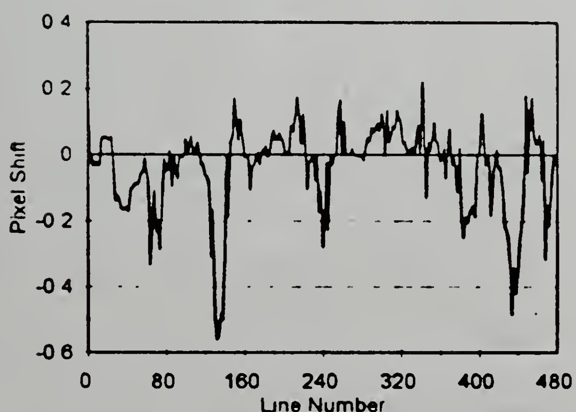


Figure 3 Line shift vs. line number

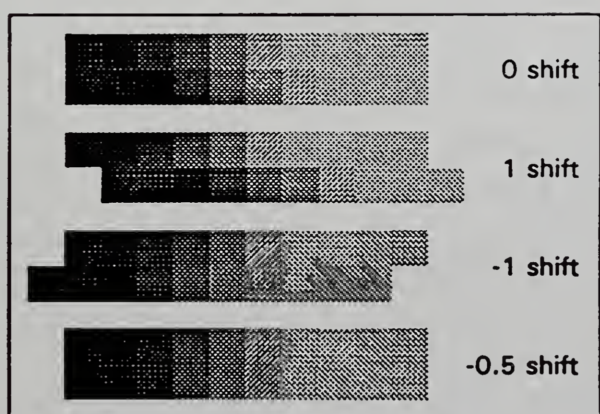


Figure 4. Integer vs. fractional line shifting.

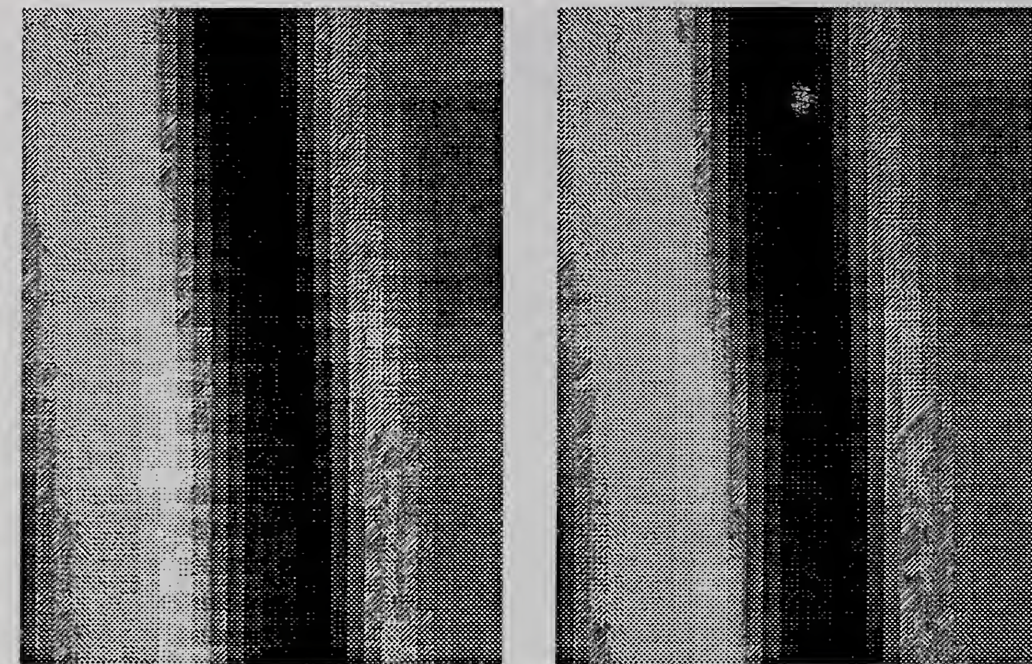

Figure 5. Feature edges before and after line shift correction.

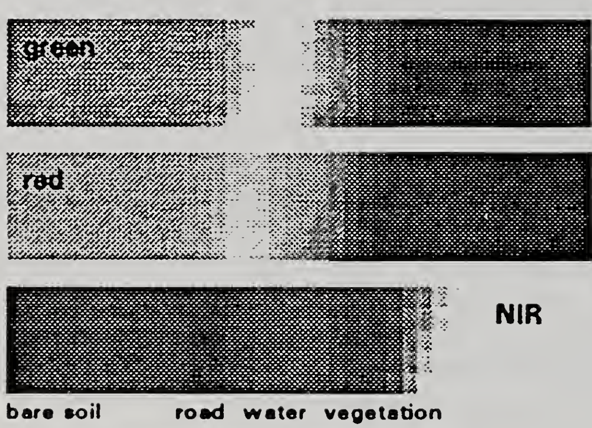


Figure 6 Typical features of MAC images

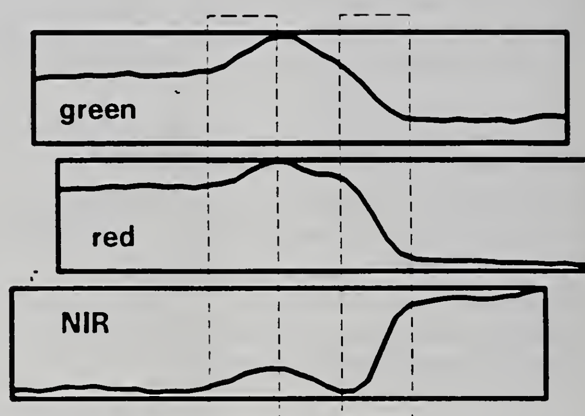


Figure 7. Feature correlations between bands.

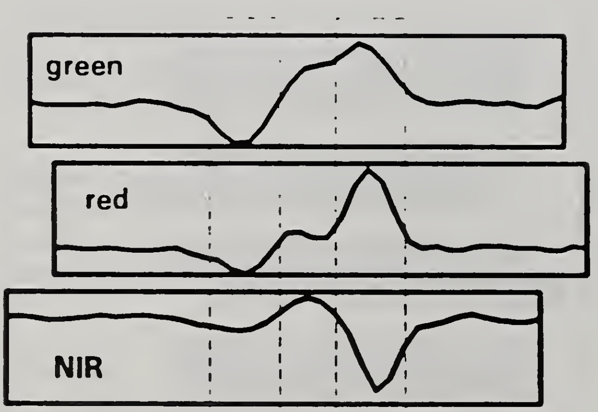


Figure 8 High-pass feature correlations

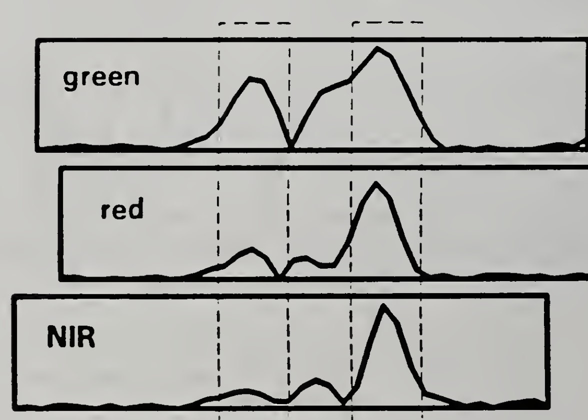


Figure 9. Absolute value feature correlations.

# AUTOMATED FARM MANAGEMENT USING REMOTE SENSING AND EXPERT SYSTEMS

# COMBINING MULTI-FREQUENCY MICROWAVE AND OPTICAL DATA FOR FARM MANAGEMENT

M.S. Moran, J. Qi, T.R. Clarke, Physical Scientists;
P.J.Pinter, Jr., Research Biologist; and T.A. Mitchell, Engineering Technician

**PROBLEM:** For more than twenty-five years, scientists have been using spectral images acquired by sensors aboard airplanes and orbiting satellites to monitor crop and soil conditions. This work has focused on the relation between surface reflectance and temperature (termed *optical* data) and such parameters as crop biomass production, crop vigor, and soil moisture. However, this work has been limited by the problems associated with measuring surface reflectance and temperature, such as cloudy weather, effects of varying solar illumination, and atmospheric interference. Recently, several new satellites have been launched which measure the backscatter of *microwave* energy from crops and soils. Data acquired in the microwave spectrum have the advantages of cloud and atmosphere penetration, and day/night acquisitions. These characteristics make microwave data appealing for agricultural applications; however, little is known about the interchangability of optical and microwave data for monitoring such parameters as crop biomass and soil moisture.

**APPROACH:** The potential for the combined use of microwave and optical data for farm management was explored based on images acquired in the visible, near-infrared, and thermal spectrum and the synthetic aperture radar (SAR) wavelengths of the Ku (~13 GHz) and C (~5 GHz) bands. The images were obtained during June 1994 and covered an agricultural site composed of large fields of partial-cover cotton, near-full-cover alfalfa, and bare soil fields of varying roughness. The work was conducted in two stages. First, the images were analyzed to determine statistical relations between the SAR backscatter and measurements of surface reflectance and temperature (Moran et al., 1995a).

Next, an SAR backscatter model was used to determine the physical relation between SAR backscatter and such agricultural parameters as green leaf area index (GLAI) and soil moisture ($h_v$) (Moran et al., 1995b). The general water-cloud model (Attema and Ulaby, 1978) represents the power backscattered by the whole canopy $\sigma°$ as the sum of the contribution of the vegetation $\sigma_v^\circ$ and that of the underlying soil $\sigma_s^\circ$:

$$\sigma^\circ = \sigma_v^\circ + \tau^2\sigma_s^\circ, \tag{1}$$

where

$$\sigma_v^\circ = AV^E \cos\theta(1-\tau^2), \tag{2}$$
$$\sigma_s^\circ = C + Dh_v, \tag{3}$$

and $\theta$ is a given incidence angle and V is GLAI. $\tau^2$ is the two-way attenuation through the canopy, expressed as

$$\tau^2 = \exp(-2BV / \cos\theta). \tag{4}$$

The coefficients D and C can be determined based on a linear regression of $\sigma°$ with $h_v$ measured for a bare soil field over a drying period. Values for A, B, and E (and C, if necessary) can be determined by fixing D and minimizing the sum of squares of the differences between modeled and measured $\sigma°$ based on eqs. (1)-(4). When values of A-E are known, it is possible to estimate values of GLAI and $h_v$ based on multi-frequency measurements of $\sigma°$.

**FINDINGS:** Findings showed that the SAR Ku backscatter coefficient ($\sigma_K^\circ$) was sensitive to soil roughness and insensitive to soil moisture conditions when vegetation was present. When soil roughness conditions were relatively similar (e.g., for cotton fields of similar row direction and for all alfalfa fields), $\sigma_K^\circ$ was sensitive to the fraction of the surface covered by vegetation. Under these conditions, the $\sigma_K^\circ$ and the optical normalized difference vegetation index (NDVI) were generally correlated (Figure 1). The SAR C backscatter coefficient ($\sigma_C^\circ$) was found to be sensitive to soil moisture conditions for cotton fields with GLAI less than 1.0 and alfalfa fields with GLAI nearly 2.0. For both low-GLAI cotton and high-GLAI alfalfa, $\sigma_C^\circ$ was significantly correlated with measurements of surface temperature ($T_s$) (figure 2). Based on the findings of correlations between $\sigma_K^\circ$ and NDVI and between $\sigma_C^\circ$ and $T_s$, the following multi-frequency SAR approach was suggested for farm management applications.

The water cloud model (eq. 1) was used to compute the backscatter of low- and high-frequency SAR data (Ku and C frequencies) for different mixed crop and soil conditions. The result was a mesh graph of Ku and C backscatter ($\sigma_K^\circ$ and $\sigma_C^\circ$), whose Cartesian coordinates could be used to determine GLAI and $h_v$. The simulated mesh graph was superimposed over the scattergram of measured values of $\sigma_K^\circ$ and $\sigma_C^\circ$ for all field borders during the June campaign (figure 3). The location of the measurements within the mesh graph were reasonable; that is, according to the ocular surveys,

1. the wet fields were generally to right and dry fields to the left;
2. fields with greater vegetation cover were located toward the top of the graph; and
3. the GLAI and $h_v$ values associated with $\sigma_K^\circ$ and $\sigma_C^\circ$ were generally within the range of values measured on-site.

A quantitative validation of the modeled results was conducted using modeled and measured $h_v$ values within selected borders of three fields. The location of field measurements within the resultant mesh graph allowed us to estimate the soil moisture for each alfalfa and cotton field within the image. Based on comparison with ground-based measurements in partially-vegetated cotton and variable-cover alfalfa fields, the modeled estimates of $h_v$ differed from measurements by 0.01 to 0.11 $cm^3/cm^3$ (figure 4).

INTERPRETATION: Considering that the model calibration was accomplished with a very limited data set, these results are encouraging. Limitations to this approach include the sensitivity of $\sigma_K^\circ$ and $\sigma_C^\circ$ to soil roughness conditions and the apparent saturation of $\sigma_K^\circ$ and $\sigma_C^\circ$ with increasing GLAI.

FUTURE PLANS: In previous work, we have derived both statistical and physical relations between measurements of SAR backscatter (in Ku-and C-band frequencies) and measurements of surface reflectance and temperature. These relations showed the potential of using SAR data interchangeably with optical data for crop and soil monitoring and farm management applications. There remain, however, some questions that will be answered with the overflights scheduled for Mission 7:

1. Is the Ku-band SAR backscatter signal independent of soil moisture conditions?
2. Do the results obtained at the 55-degree incidence angle hold for a variety of incidence angles?
3. Could multi-incidence SAR data in a single frequency (Ku-band) be used instead of multi-frequency SAR data at a single incidence angle in this application?

We propose to answer questions 1 and 2 by arranging for a variety of soil moisture and surface roughness conditions at MAC with simultaneous acquisitions of Ku- and C-band SAR images in January 1996. An attempt will be made to produce fallow fields of similar soil roughness and varying soil moisture conditions. Regarding question 3), we will make measurements of soil moisture conditions and vegetation biomass and green leaf area index (GLAI) in alfalfa and wheat fields during the overpass. These data will be used to test the soil moisture and GLAI estimates made with the SAR/modeling approach for different incidence angles. It will also allow the first application of the approach to a wheat canopy.

COOPERATORS:

Alain Vidal, Denis Troufleau, CEMAGREF-ENGREF Remote Sensing Laboratory, Montpellier, France;
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Bob Huelskamp, AMPS manager, Sandia National Laboratories, Albuquerque, New Mexico.

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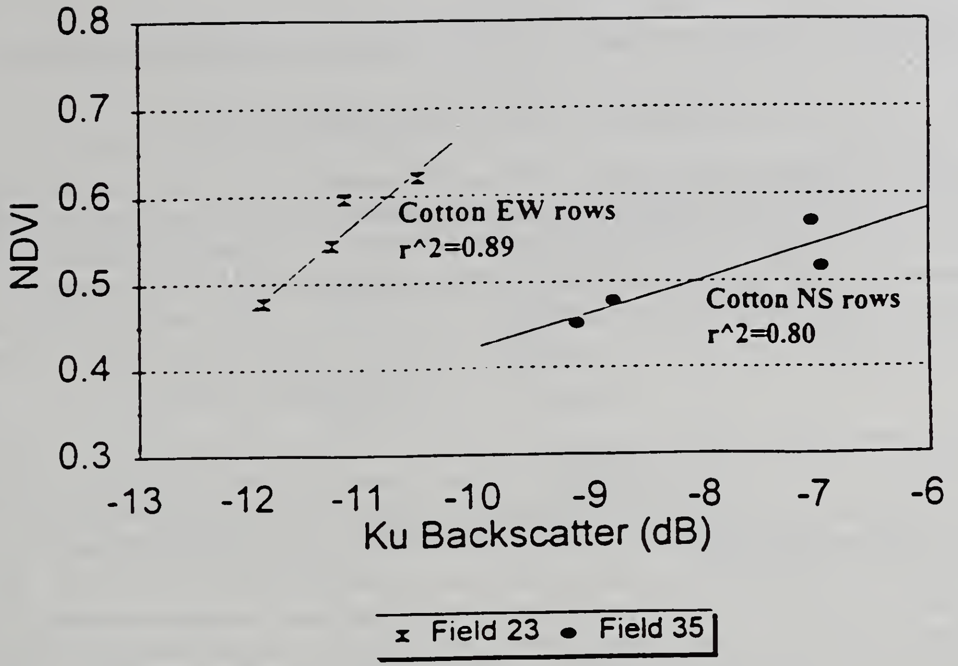


Figure 1. Correlations between $\sigma^{\circ}_{c}$ and NDVI for fields 23 and 35. For these cotton fields, the within-field soil roughness was constant, and $V_c$ varied by border from 20-50% in field 23 and from 10-30% in field 35.

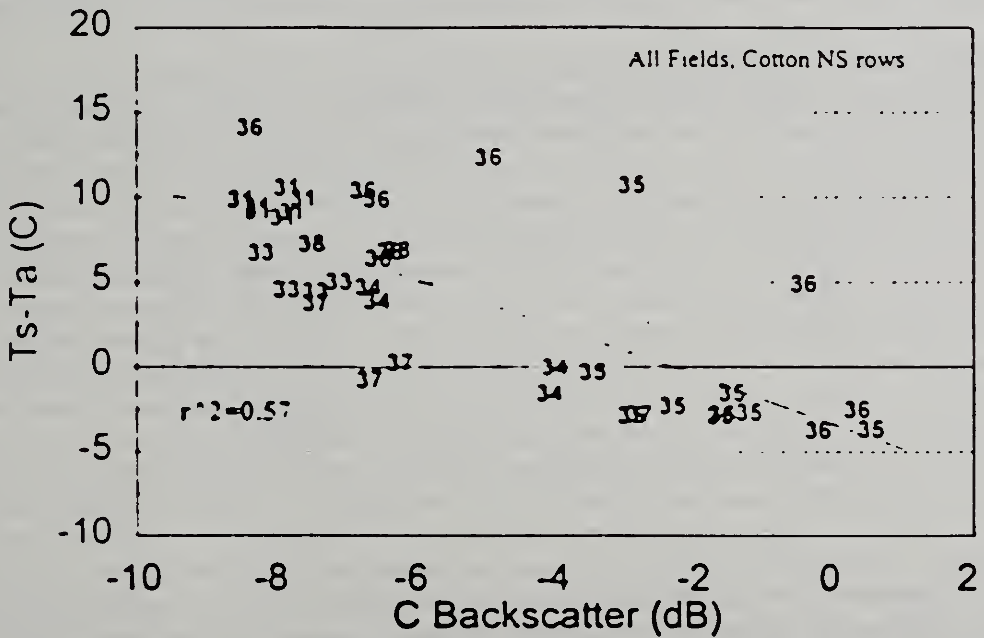


Figure 2. Correlations between $\sigma^{\circ}_{C}$ and $T_s$-$T_a$ for cotton fields of similar row direction. The numbers represent field identifications and are used in lieu of solid markers.

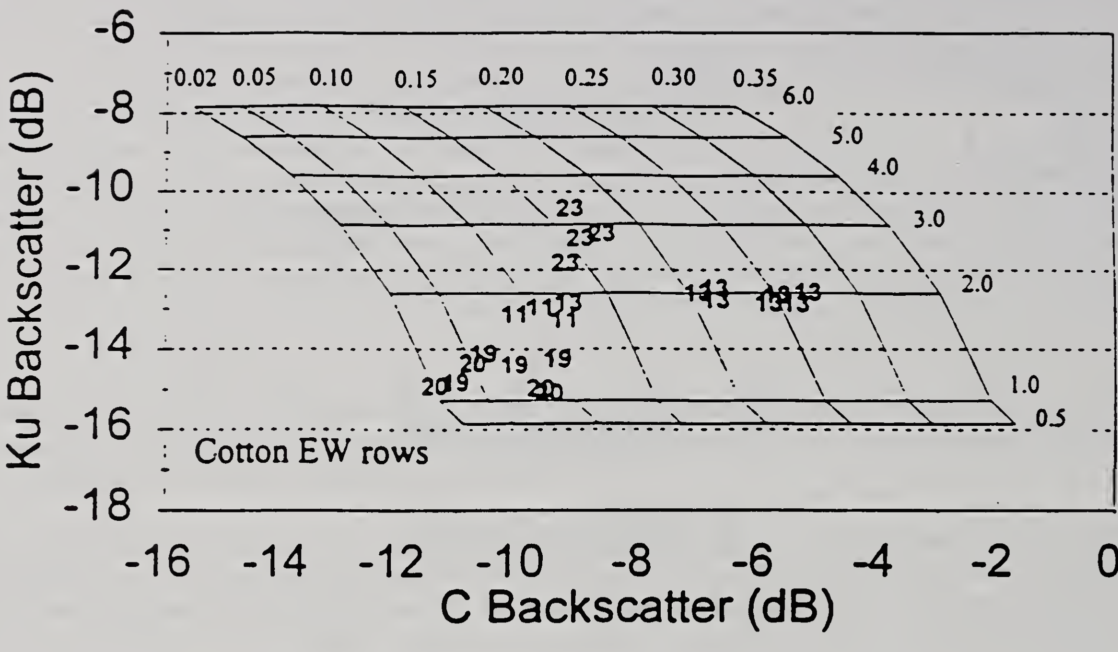


Figure 3. Mesh graph of $\sigma_K^\circ$ and $\sigma_C^\circ$ for cotton with EW row orientation at MAC during the June overflights. The numbers represent field identifications and are used in lieu of solid markers for the locations of the $\sigma_K^\circ$ and $\theta_C$ measurements for border within each numbered field. The solid lines define modeled backscatter for values of GLAI (listed on the right) and soil moisture (listed on top), derived from the calibrated water cloud model.

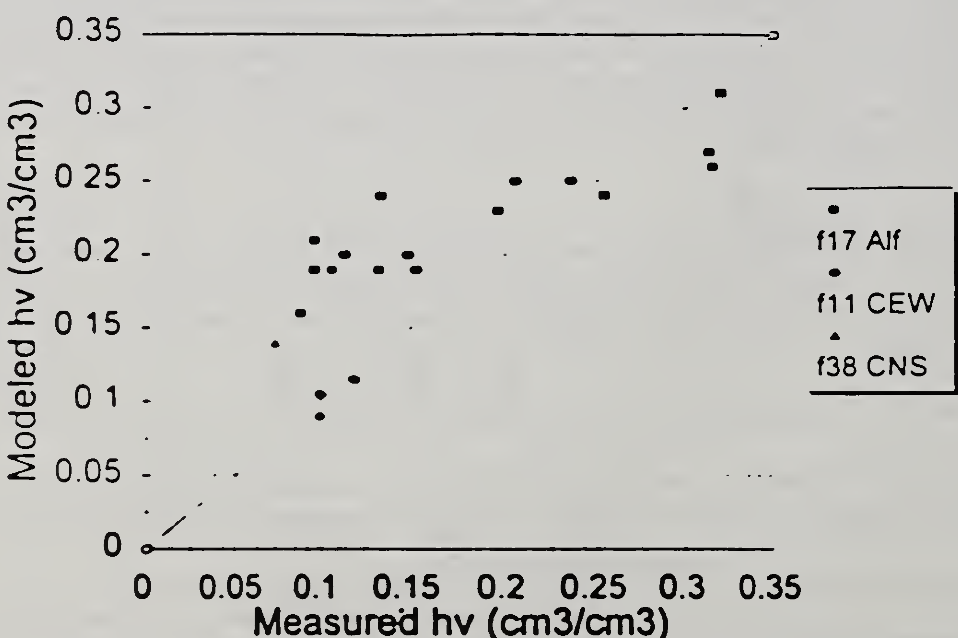


Figure 4. Comparison of modeled and measured soil moisture ($h_v$) values within selected borders of three fields: field 17 (alfalfa), field 11 (cotton with EW rows), and field 38 (cotton with NS rows).

# COUPLING REMOTELY SENSED DATA TO A MESOSCALE ATMOSPHERIC MODEL

J.J. Toth, Meteorologist; and M.S. Moran, Physical Scientist

**PROBLEM:** Remotely sensed data can be used to estimate surface sensible and latent heat fluxes over an entire region. Within the Basin and Range Province of southern Arizona, the potential benefits of accurate estimates include not only improved local crop diagnostics, but also a better determination of feedback effects on the regional climate. Many existing flux-estimate techniques make approximations that are questionable in an area of complex topography and sparse vegetation. For example, sparse vegetation can be addressed by assuming that the atmosphere is horizontally homogeneous. While such an assumption may be reasonable for small (e.g., 20 $km^2$) areas, it certainly cannot be extended to cover both mountain range and basin.

**APPROACH:** To estimate heat fluxes over a large, heterogeneous region, we are coupling the Regional Atmospheric Modeling System (RAMS) model with remotely-sensed surface parameters. The two parameters primarily used were (1) the effective surface temperature and (2) the NDVI vegetation index. The first of these, effective surface temperature, was explicitly predicted in the model as a weighted average of the model vegetation temperature and the model bare soil temperature. The second, NDVI, did not have an exact counterpart in the model, but was used as an indicator of fractional vegetation coverage. Recognizing that NDVI may be influenced by other vegetation characteristics, the vegetation-coverage estimates were treated as containing a certain degree of error. The fractional coverages were adjusted by amounts no more than 0.20 above or below the original estimates. The purpose of the adjustments was to produce model surface temperatures in agreement with the Landsat satellite observations. As an initial test of this approach, the model was run for a two-dimensional vertical cross-section extending across the San Pedro basin. The details of one model run are shown The specified surface elevation and fractional vegetation coverage are at the top of figure 1. Only the 1-km horizontal grid spacing is shown. Near the center of the basin a riparian area, less than 1 km wide, was resolved with an inner, nested grid. On the 1-km grid, the soil moisture was increased for the two points nearest the river. The model was initialized with a radiosonde sounding taken near the time of the satellite overpass. The wind below mountain-top was initialized calm, and the model fields evolved for a full 24 h before comparison with the satellite data. All temperatures were converted to potential temperature (i.e., adjusted to sea-level using a dry-adiabatic lapse rate).

**FINDINGS:** By 10:30 MST (the time of the satellite overpass) the mountains, serving as elevated heat sources, caused the model to generate moderate (5 m/s) surface winds along the mountain slopes. Surface winds near the center of the basin remained nearly calm. The surface air temperature was highest over the mountains, consistent with constant heating of air parcels as they moved from the basin to the mountains. Except for evaporation near the river, nearly all of the model latent heat flux was due to transpiration. Over the basin, the total flux of latent heat was very small (30-40 $W/m^2$), except for higher amounts at the river. Along the mountain slopes, the combination of moderate winds, 70% vegetation cover, and correspondingly higher leaf area caused the latent heat flux to exceed 300 $W/m^2$. At the mountain top, where the wind again became nearly calm, the latent heat flux was reduced to 150 $W/m^2$. The sensible heat flux followed a pattern roughly opposite that of latent heat. The exception was a trend toward higher sensible heat moving from the center of the basin toward the mountains. There was a corresponding trend toward lower bare soil temperatures (figure 2). Both of these trends are associated with increased wind speeds which caused a shift in the surface energy budget from soil heat flux to sensible heat flux. The vegetation temperature (not shown) was consistently 2-3 degrees warmer than the air temperature, except for the slope regions with high transpiration, where the vegetation cooled to approximately the same as or even slightly cooler than the air temperature. The vegetation was naturally much cooler than the dry bare soil, and so the warmest effective temperatures were generated over the basin away from the river. These temperatures were slightly cooler than but within 2 K of the satellite-observed surface potential temperatures. The river temperatures on the inner grid (not shown) were also in good agreement with the satellite data. The mountain temperatures, ranging from 321 to 326 K, were roughly 2 degrees warmer than the range of satellite temperatures.

The vegetation coverage over the mountains was initially estimated at 60%. Because the effective temperatures were too high, the coverage was increased to 80%. This yielded effective surface temperatures in excellent agreement with the satellite data. But it also generated latent heat fluxes in excess of 400 $W/m^2$. The radiosonde data, which sensed the upper branch of the mountain circulation, returning from mountain-top, indicated that the 70% as well as the 80% vegetation coverage produced too much moisture flux from the mountains.

**INTERPRETATION:** The two-dimensional results were somewhat unrealistic due to the unnatural constraints of the boundary conditions. However, these simulations highlighted the importance of horizontal inhomogeneities in the atmosphere. For example, if the winds and temperatures across the basin were assumed to be constant, then the sensible heat flux would be estimated as positively correlated with the surface skin temperature. The model results indicated just the opposite correlation across the lower basin. The model transpiration appeared to be overly sensitive to the combined effects of wind and leaf area; that is, transpiration was too low over the basin and too high over the mountains. The leaf area was set, based on previous studies, at approximately seven times the fractional coverage of vegetation. This value may require downward adjustment over the mountains. The mountain winds may also be too high. Full, three-dimensional simulations will be required to resolve this uncertainty.

FUTURE PLANS: Full, three-dimensional model simulations with accurate boundary conditions will be required. The boundary conditions can be obtained from large-scale operational model analyses generated by the National Weather Service. But these operational analyses use heavily smoothed topography. In order to resolve the effects of individual mountain ranges, model simulations with 4-km and 1-km grid spacings will be needed over limited domains. The model grids should be referenced to UTM coordinates so that the model output can be incorporated into a GIS analysis system.

There are several parameters that influence the model surface temperature (vegetation coverage, leaf area index, soil type, surface and deep soil moisture). Consideration should be given to lumping these together into a single adjustable parameter that could be related to NDVI and perhaps other remotely-sensed data. The disadvantage of this approach is that it becomes difficult to relate this single adjustable parameter to measurable quantities.

Finally, to be really valuable the flux estimates need to be made routinely. The link between operational analyses and small-scale detail cannot always depend on a 3-D atmospheric model. A solution might be to run model simulations for certain climatologically favored patterns. The results from these detailed simulations could be retrieved and used repeatedly on a routine basis.

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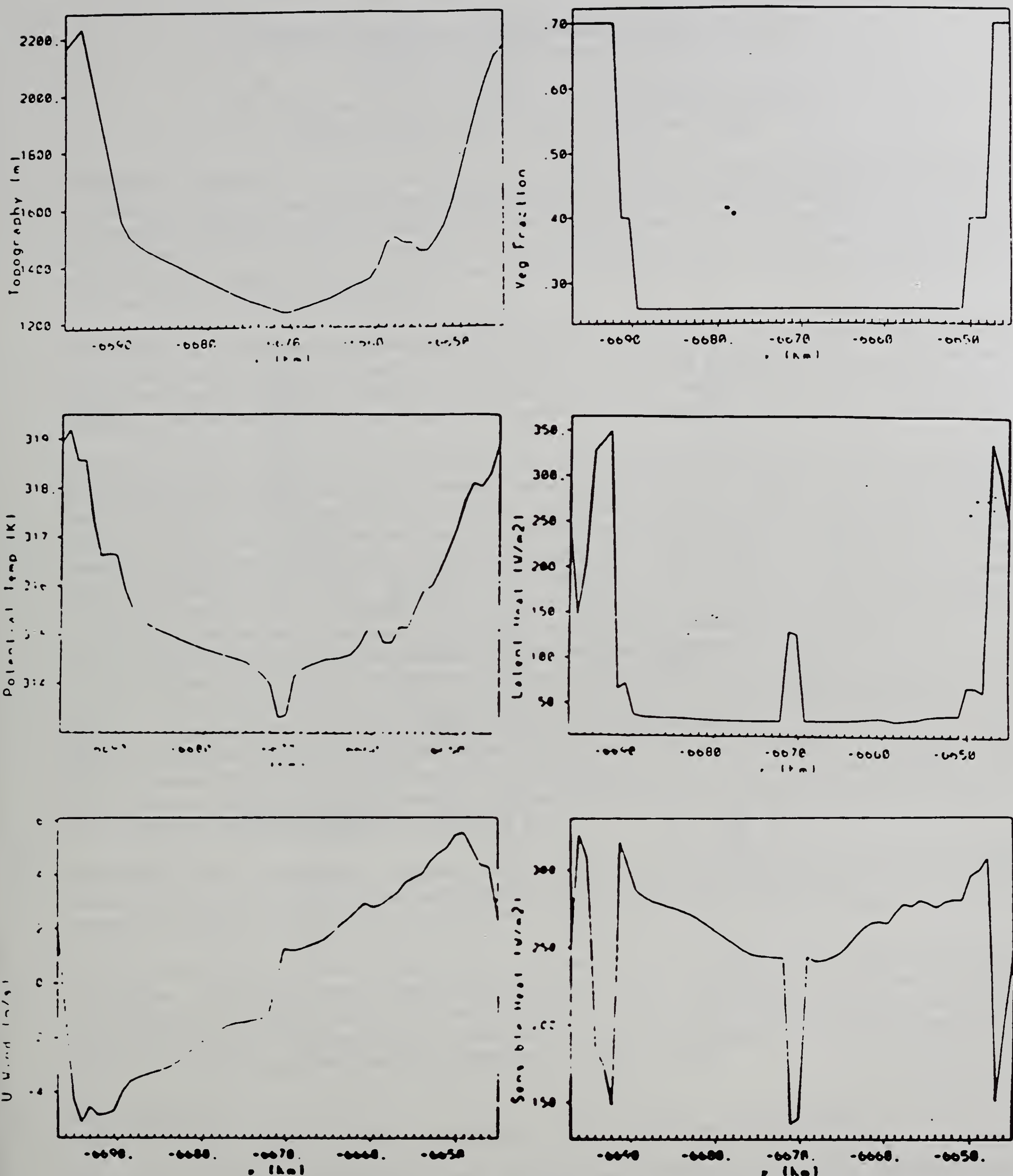


Figure 1. Model output for a cross-section across the San Pedro Basin. The tick marks along the horizontal axis are the model grid points. Plotted quantities are labeled. The topography and vegetation were specified, other quantities were forecast. The air potential temperature and horizontal wind are for the first model level above the ground. A positive wind is blowing toward the right.

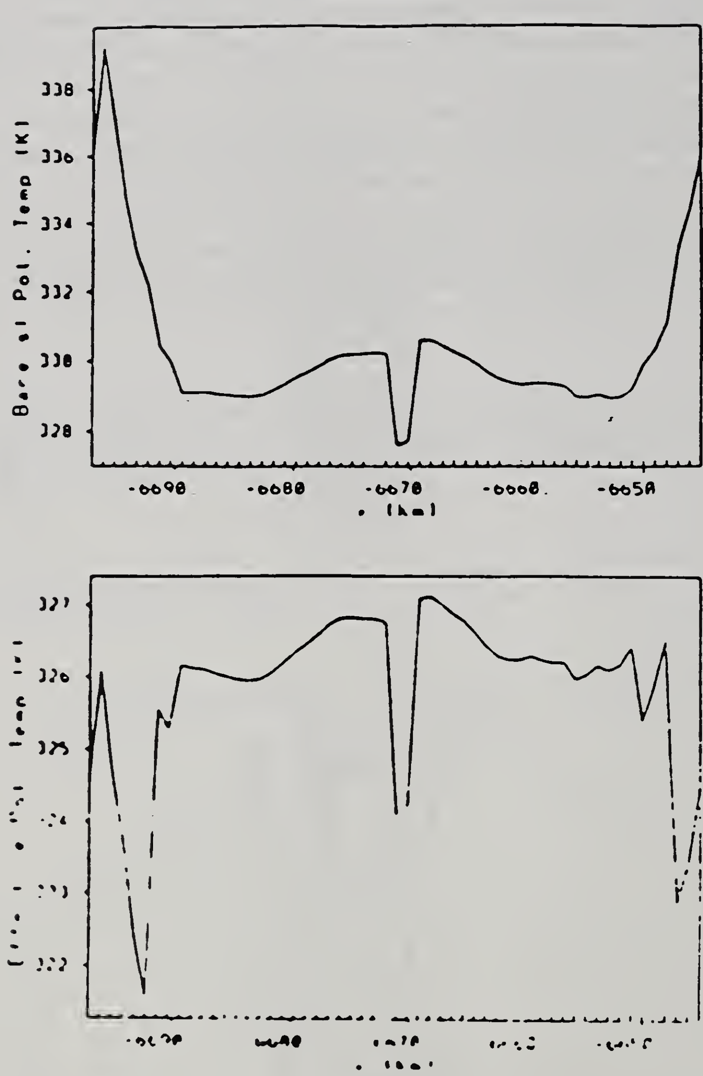


Figure 2. Same as Figure 1, but for the potential temperatures of (1) the bare soil and (2) the bare soil and vegetation combined.

# IDENTIFICATION OF NEW METHODS TO APPLY REMOTE SENSING FOR FARM MANAGEMENT

E. M. Barnes, Agricultural Engineer; T. R. Clarke and M.S. Moran, Physical Scientists; and P. J. Pinter, Jr., Research Biologist

**PROBLEM:** Researchers have demonstrated several ways in which remotely sensed data can be used to characterize crop conditions; however, operational application of this technology at the level of production agriculture is still limited. Factors that have contributed to this limited adoption include the availability and cost of the data and the lack of necessary tools to interpret the data for decision making purposes (Jackson, 1984; Moran, 1994). The objective of this project is to identify methods to expand the products available from remotely sensed data in order to maximize their utility and cost effectiveness for farm management applications.

**APPROACH:** The problems facing agricultural producers and service providers are being identified to determine areas where remote sensing techniques can be applied to provide solutions. This is being accomplished through interaction with Cooperative Extension personnel, contacts with agricultural consultants, and informal interviews with producers. Additionally, methods that use remote sensing data to enhance other farm management technologies are being explored.

**FINDINGS:** While this project is in its initial stages, two areas currently show potential to develop a synergistic relationship with remote sensing to assist farm managers and consultants. The first is related to crop growth simulation models. These models have been developed to predict crop growth in response to factors such as meteorological conditions, water stress, and available soil nutrients. Systems have been developed to use these models to identify management practices that optimize the use of water and farm chemicals for agricultural production (Jones and Ritchie, 1990; Hoogenboom and Boote, 1992). However, the application of these models has been limited by the complicated calibration procedures that must be conducted before they can be applied accurately with a new variety or under different site conditions. Development of automated procedures to process remotely sensed data for comparison with the crop model's predictions will increase the ease and accuracy with which these models can be applied.

The second area identified is site-specific agriculture, which uses a global positioning system (GPS) to link agricultural equipment with a geographic information system (GIS). The GIS is a spatial data base containing information such as soil type, crop type, and fertilizer requirements (Blackmore, 1994). The information in the GIS can then be used to vary application rates according to the specific needs of a particular location in the field. A limitation to this farming system is the vast amount of data needed to maintain the GIS. Remote sensing has the potential to supply and supplement many of these data needs. Site-specific farming naturally complements remote sensing, as the tools (GIS and GPS) needed to utilize aircraft- or satellite-based imagery are already in place.

**INTERPRETATION:** The synergistic combination of remote sensing with other technologies promises to increase the adoption rate of new, more efficient farm management practices. By extending the products that can be derived from remotely sensed data, the economic return from this data to the agricultural producer can be increased.

**FUTURE PLANS:** Efforts to interact with the agricultural community to identify and develop remotely sensed products will continue. A prototype system to integrate remotely sensed data with a cotton growth simulation model will begin in the near future. Definition of specific remote sensing products that will serve site-specific agriculture is also planned in the coming months. As these areas are developed, methods to combine all three technologies (remote sensing, crop models, and site-specific agriculture) will be considered.

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# GERMPLASM IMPROVEMENT AND CULTURAL DEVELOPMENT OF NEW INDUSTRIAL CROPS

# GUAYULE LATEX EXTRACTION AND GERMPLASM IMPROVEMENT

F.S. Nakayama, Research Chemist; T.A. Coffelt, D.A. Dierig,
and A.E.Thompson (Collaborator), Research Geneticists

**PROBLEM**: Much interest has been generated since it was reported that latex from the semi-arid adapted guayule plant was hypoallergenic, unlike Hevea latex which can cause mild to severe allergy reactions. Unfortunately, sufficient quantities of latex for latex testing and making medical products are not presently available. Reliable information is lacking on the best method for extracting latex from shrubs and its preservation after extraction. Similarly, no data are available on the yield potential of the various guayule lines, which were selected and developed for optimizing solid rubber and not latex rubber. Our research efforts, started in 1994, continue to be (1) the development of guayule latex rubber extraction methods for optimizing its quality and quantity (produce sufficient quantities of latex for testing and fabrication), and (2) the improvement of guayule lines for maximizing latex yields.

**APPROACH**: Latex Extraction: Laboratory procedures, with potential for scaling up the process, that include chemical and physical variables, will be used to determine the extractability of latex from the shrub. Shrubs will be cut into smaller pieces so they can be handled by laboratory blenders. Water-based latex extracting solution will consist of an antioxidant and binder or complexer for the phenolic resins. Microbiological inhibitors will be used as needed. The macerated plant material and extractant will be filtered and then stabilized by ammonification. The raw latex then will be concentrated with a cream separator system and followed with further concentration with the creaming procedure. During this testing stage, the latex obtained will be made available to the various researchers needing the raw latex. In addition, the raw latex will be purified, primarily to remove the resin materials that are closely associated with the rubber polymer. Various approaches can be taken for this objective (fig. 1), and the one that is simplest and most economical will be selected for the large scale production of latex.

Because of limited facilitates during the laboratory renovation, specific cooperative agreements will be made with the universities for developing latex analysis techniques and for shrub analysis for latex and bulk rubber and resin contents. Latex extractability of existing guayule lines will be determined from which the appropriate selections and yield enhancement breeding procedures can be followed.

Guayule Germplasm: Field tests were conducted at the Maricopa Agricultural Center (MAC) and Marana Experimental Station to determine the genotype interactive effects with planting method (transplanting vs. direct seeding), stem size, and field storage time after harvest. Planting method evaluations were conducted on new plantings made in 1995, while the stem size and field storage tests were conducted on established plants. Lines developed from tissue culture were field transplanted at MAC to try to reduce within line variability.

**FINDING**: Latex Extraction: Adequate quantities of latex material were produced to supply our cooperators working with the biological, physical and chemical properties of the latex. One cooperator was able to develop a laboratory method for determining latex in small amounts of plant materials. The procedure is being used for evaluating latex yield potentials of the various lines of guayule. For latex extraction, we found that storage of shrub for one week under refrigeration prevented the loss of latex. In addition, refrigeration of the raw extracted latex before centrifuge separation helped in the extraction procedure. The cream separator could remove about 50% of the latex present in the raw, freshly ground and filtered preparation, which had a latex concentration between 0.5 and 1%. The latex concentration varied from 15 to 20%. Cream washing (fig. 1) increased the latex concentration to 40%. The higher concentration is needed by industry for their latex product preparation. Creaming helped to decrease the resin content of the latex to about 13%. The Mooney values of the coagulated latex were approximately 65% of Hevea latex, but we do not know at present how this difference will affect the final latex product.

Guayule Germplasm: Both direct seeding and transplanting could be used for establishing all the germplasm lines under study. The plant size for the spring planting was larger for the transplanted than the direct-seeded stands, but they were equal in size by fall. Lines varied significantly in growth rate. Results from stem size studies on two improved lines (O16-1 and G7-11) showed that most (76%) of their latex was in stems 2-10 mm in diameter. G7-11 had significantly higher fresh and dry weights than O16-1, whereas O16-1 had a significantly higher percentage of latex. Thus, the total latex yield of the two lines was equal. Results from field storage tests showed significant losses in latex occur within 24 hours after harvest.

**INTERPRETATION:** Latex Extraction: Latex extraction efficiency could be improved by further modification in the solvent composition and better separation equipment. Coagulation of part of the latex in the separator disks could possibly be prevented by use of stabilizers, which would not affect processing further down the fabrication process. Resin removal also has not been optimized, and additional work needs to be done to improve latex quality.

Guayule Germplasm: Guayule can be established either by direct seeding or transplanting seedlings. Direct seeding is much cheaper than transplanting. Some factors affecting successful stand establishment by direct seeding were seed quality (% germination), planting depth, soil and air temperatures at and following planting, and irrigation method. Direct seeding can be used with furrow irrigation, but stand establishment is easier with sprinkler irrigation. Young, direct-seeded stands are extremely susceptible to damage by heavy rains. The optimal conditions for success in direct seeding are warm temperatures during and after spring or fall planting, use of sprinkler irrigation, and no rainfall during the establishment period. The finding that the higher concentration of latex resides in the smaller stems allows us to be more flexible on harvesting methods. For example, hedging and pollarding of plants, instead of whole-plant harvest, are possible. Both methods allow for plant regrowth without need for replanting and permit an earlier harvest for the following cycle. The finding that latex is rapidly lost following harvest means that more work needs to be done on post-harvest technology to maintain maximum latex. More work needs to be done on reducing the within line variability. Reducing this variability could significantly increase latex yield and lead to an improved possibility of guayule commercialization.

**FUTURE PLANS:** Latex: Continue to explore the extraction process to increase the efficiency of latex removal and controlling resin content. This involves further work on extraction solution composition. Plant preparation procedure could be simplified and possibly involve stabilizers and antidegradants to help in the actual latex separation process. Because the extraction of latex is a water-based process, we will look at various recycling schemes for water conservation. Develop in-house capabilities for measuring resin content and composition, and for determining the physical properties of the latex.

Guayule germplasm: Continue to evaluate direct seeding and transplanting for stand establishment, harvesting techniques, and to reduce within line variability. These studies involve close cooperative work with scientists at the various locations involved in guayule culture. Continue to develop new lines of guayule with a higher latex yield, primarily through a combination of higher latex concentration and biomass.

**COOPERATOR:** K. Cornish, USDA-ARS-PWA, Albany, CA; W. Coates, J. Hoffman, and D. Stumpf, Office of Arid Land Studies, University of Arizona; D.T. Ray, Plant Science Dept, University of Arizona, Tucson, AZ; W.W. Schloman, Jr., Department of Polymer Science, University of Akron, Akron, OH; M. Foster, Texas A&M University, Ft. Stockton, TX; R. Backhaus, Arizona State University, Tempe, AZ.

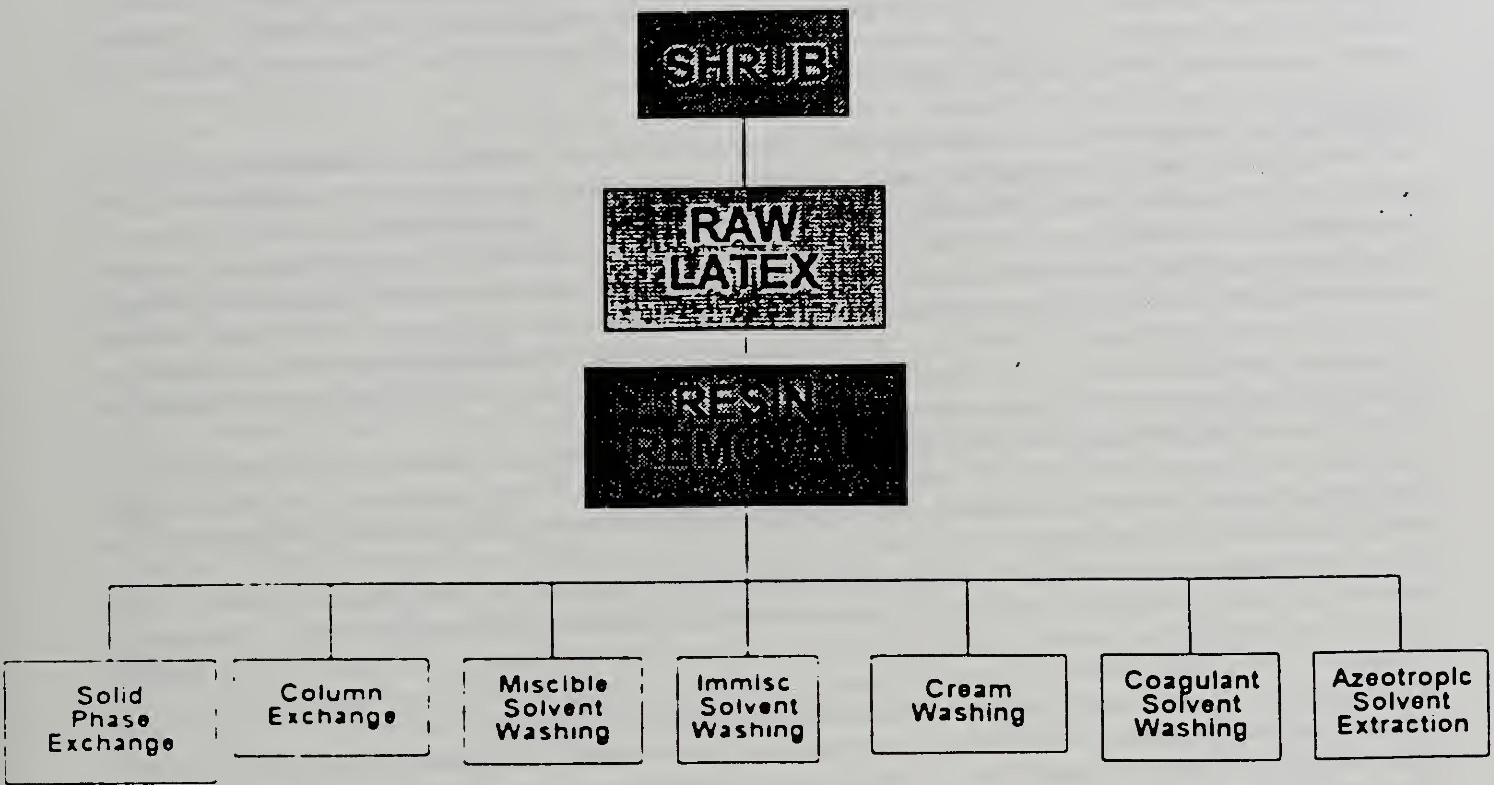


Figure 1. Various schemes for purifying guayule latex.

## LESQUERELLA GERMPLASM IMPROVEMENT AND COMMERCIALIZATION STATUS

D.A. Dierig, T.A. Coffelt, and A.E. Thompson, (Collaborator), Research Geneticists;
and F.S. Nakayama, Research Chemist

**PROBLEM:** Lesquerella has potential as a new industrial hydroxy fatty acid oilseed crop that could contribute significantly to U.S. agriculture by providing diversifacation from traditional crops and improve the general economy of the country. Since early 1970, the U.S. has relied exclusively on imports of castor for the supply of hydroxy fatty acids used in many types of industrial applications. Imports of castor oil and derivatives amount to more than 65,000 tons per year at a value exceeding $100 million per year. The unique chemical structure of the oil from Lesquerella offers distinct advantages for development of new industrial applications as well as a partial replacement for castor oil. At present, one species native to the southwest is being developed. Other species may also have potential as sources of hydroxy fatty acids in other geographical locations. Many species of *Lesquerella* and a closely related genus with this same seed-oil, *Physaria*, are becoming extinct. The germplasm base of these species needs to be expanded to preserve the diversity.

Continued cooperative interaction with universities and industry, which this laboratory initiated, must be maintained. The focus of our research is to collect, evaluate, and improve, through plant breeding, Lesquerella germplasm and develop appropriate cultural and water management practices.

**APPROACH:** Germplasm of *Lesquerella* species were collected in Oklahoma, Tennessee, and Alabama in 1995. Along with seed collection, data were taken on seed size, growth habit, and other plant characteristics. Flower buds, if available at the necessary meiotic stage, were collected for chromosome counts. Seed oil contents and composition were determined. Evaluations and seed increases of these collected accessions were made. Fifty populations of *L. fendleri* were field grown. When plants began to flower, screen cages were placed over individual plots and were supplied with a nucleus of honey bees for pollination. Insects are necessary for seed production in Lesquerella. The cages prevented accessions from cross pollinating, so seed lines could be maintained without contamination. Plant growth measurements were taken throughout the season. After harvest, seeds from each accession were analyzed for oil content and composition, and gum content of the seed coat.

Three recurrent populations for increased oil content, increased hydroxy fatty acid content, and oil and hydroxy fatty acid yields were repeated for the 1994-1995 season. This is the third generation of these populations. Five hundred plants from each population were harvested and analyzed. The highest 10% of the population was chosen and planted for new recombinations and further selection.

Plants segregating for a maternally inherited yellow versus an orange seed coat trait were planted at USWCL. Plants producing yellow seed were selected at harvest. This trait may have an importance in the cosmetic industry. Decoloration from the seed coat pigment is present in the oil and must be removed by hydrogenation. The oil from these lines may be lighter in color and eliminate this extra processing. Quality and quantity of oil and gums from these lines will be examined when sufficient quantities of these materials become available.

Seed of autofertile progeny (plants that do not require insects to produce seed) were planted in the greenhouse this fall. These selections include germplasm from our program and from our industry collaborator, Mycogen Plant Sciences. These plants will be kept in isolation to verify that they are autofertile. After verification, seed will be increased.

Molecular markers are being developed using a Polymerized Chain Reaction (PCR) technique called RAPDs. The methodology for DNA extraction has been completed, and primers producing polymorphisms are being screened. Codominant isozyme markers are continuing to be used in genetic inheritance studies such as male sterility.

We have been attempting to produce fertile hybrids between *L. fendleri* and other species from this genus. Controlled crosses were made using *L. lindhimeri* and *L. gracillis* as pollen parents. Both of these species have higher oil contents and different oil profiles than *L. fendleri*.

**FINDINGS:** Five species, 11 accessions, were collected from Tennessee, including *L. densipilia* (2 accessions), *L. globosa* (2 accessions), *L. lescurii* (2 accessions), *L. perforata* (2 accessions), *L. stonesis* (3 accessions). *L. lyrata* (1 accession) was collected in Alabama. In Oklahoma, *L. angustifolia* (3 accessions), *L. auriculata* (1 accession), *L. gordonii* (9 accessions) *L. gracillis nuttallii* (4 accessions), *L. ovalifolia ovalifolia* (6 accessions), and *L. ovalifolia alba* (3 accessions) were collected. Seed oil content and fatty acid composition profile are being analyzed.

Accessions of *L. fendleri* being evaluated at USWCL had diverse growth habits, ranging from upright to prostrate. The number of days until the first flower ranged between 119 to 154 days. Seed weights ranged between 0.51 to 1.2 g / 1000

seed. Seed oil content ranged between 17.5 to 28.7%. Seed oil composition is still being evaluated. Preliminary seed coat gum contents have ranged between 9.2 to 14.7%.

The recurrent population for high oil content ranged between 14 to 37%. The range from the previous year was between 18 to 32%. The population mean (500 samples) was 26.5%. Over the past three years, we have increased seed oil content with this breeding strategy from 22 to 26%. The population for high lesquerolic acid content ranged from 45.9 to 64.2%. The population mean was 54.5%. Lesquerolic acid yields ranged between 11 to 20%. The mean of this population was 15.3%. All populations had an increase in the trait being selected compared to the previous year. Samples from an unselected check population are also being analyzed to compare with this population. Plants containing seed with only yellow seed coats were identified in the field. Seed oil contents of these plants were not statistically different from the orange-brown seeded plants. Autofertile plants were also identified in the greenhouse. Putative hybrids between *L. fendleri* x *L. lindhimeri* and *L. fendleri* x *L. gracillis* were produced.

**INTERPRETATION:** A major role of the USWCL research effort is to provide leadership in new germplasm collection, evaluation, genetic enhancement, and development of improved varieties or hybrids. This aspect of our program is being achieved. Full scale commercialization efforts are now underway involving other USDA agencies, universities, and private industries.

Fewer accessions than the two previous years were collected. Many of the historical locations where these species have been found in the past were no longer available. The list of species on the verge of becoming endangered is increasing, and those species in the eastern U.S. are following similar trends. This fact makes this work even more important since soon many of these species could become extinct. The germplasm collections help preserve this diversity.

An adequate representation of the native eastern U.S. populations has been completed in this year's collection. Through the past 3 years of collection, we have added 10 species not previously present in Germplasm Resources Information Network (GRIN) and 87 new populations of *L. fendleri*. This greatly improves the amount of diversity from which we can draw in our breeding program. It also will be important for the future development of potential markets for other Lesquerella species containing other types of hydroxy fatty acids.

The achievement of increasing oil content through recurrent selection is encouraging. The range of oil content for *L. fendleri* collected in the wild is not as high what has been achieved in the recurrent population. This demonstrates that the actual genetic potential is much greater than what is represented in the initial screening of the populations from the wild.

Continued research on water use efficiency and timing of water application is clearly needed along with other agronomic research involving fertilization, dates of planting, and harvesting. The additional support from the "Advanced Materials from Renewable Resources Program," DOD, through USDA-CSRS-OAM, will facilitate this by providing funding for our university cooperators. The infusion of AARC funding into our program will greatly help the germplasm evaluation program.

**FUTURE PLANS:** Germplasm collections in 1996 are planned for Utah, Wyoming, and Colorado. A recollection in Oklahoma is also planned for additional accessions of *L. auriculata*. More than half of the *fendleri* collections, along with a limited number of other species, have been evaluated and seed increased. The remainder will be completed in 1996 at this location.

The next generation of the recurrent selection for improved oil and fatty acid content has been planted. Seed will be harvested and analyzed at this laboratory in June 1996. Seed and oil characteristics of yellow seed coat lines will be studied this season along with continued development of autofertile lines. We plan to hire a postdoctoral research associate to develop molecular markers for breeding.

**COOPERATORS:** R. L. Roth, Univ. Arizona, Tucson, AZ; J.H. Brown, J.D. Arquette, and R. Kleiman, International Flora Technologies, Gilbert, AZ; M. Pollard and L. Sernyk, Mycogen Plant Sciences, San Diego, CA; E. H. Erickson, USDA, ARS, Carl Hayden Bee Research Laboratory, Tucson, AZ; T.Abbott and B. Phillips, USDA, ARS, NCAUR, Peoria, IL.

## CULTURAL MANAGEMENT OF LESQUERELLA: WATER AND STRESS MANAGEMENT

D.J. Hunsaker, Agricultural Engineer; W.L. Alexander, Agronomist;
D.A. Dierig, Research Geneticist; and F.S. Nakayama, Research Chemist

**PROBLEM:** Efficient management of irrigation water to achieve optimum yield is essential to the commercialization of *Lesquerella fendleri*, a plant native to the southwestern U.S. that contains high amounts of a unique oil for making lubricants, resins, waxes, nylons, plastics, cosmetics, and other products. Prior studies have indicated a seasonal water requirement of about 600 mm for lesquerella in central Arizona. However, scheduling irrigation time and amount for the crop has not been established.

A computer-based irrigation scheduling information system (AZSCHED) is presently used in Arizona to schedule irrigation for traditional crops such as wheat and cotton. The irrigation scheduling software is menu-driven and relatively easy to use. However, one of the primary elements of AZSCHED is a crop coefficient curve that relates the crop's evapotranspiration ($ET_c$) throughout its growing season to a meteorological-based, grass-reference evapotranspiration ($ET_o$). Thus, before AZSCHED can be used for scheduling lesquerella, a specific crop coefficient curve must be developed. The first objective was to derive a crop coefficient curve for lesquerella. The second objective was to incorporate the curve with AZSCHED and evaluate the effectiveness of the irrigation scheduling program for lesquerella. The third objective was to determine the effects of allowable soil water depletion from 40 to 60% on the seed yield and oil content of lesquerella.

**APPROACH:** AZSCHED uses a soil water balance to predict the time and water application amount for irrigations during the season. A user establishes an allowable soil water depletion level at which irrigations will be given and provides an estimate for the system irrigation efficiency. The program estimates crop water use during the season from a crop coefficient curve that expresses the ratio of daily $ET_c$ to daily $ET_o$ [$k_c$] as a function of accumulated heat units, also called growing-degree-days (GDDs). Local meteorological data is used to calculate $ET_o$.

Irrigation studies were conducted by the USWCL during the 1991-92, 1992-93, and 1993-94, seasons to obtain data on lesquerella crop coefficients during the seasons. The data were used to derive a lesquerella crop coefficient curve.

During the 1994-95, lesquerella season, the curve was used in the AZSCHED program to schedule irrigations. The experiment was conducted at The University of Arizona Maricopa Agricultural Center (MAC). *Lesquerella fendleri* was planted on the flat in 18 11- by 15-m plots on September 30, 1994. The seeding rate was 6.7 kg seed per ha. Immediately after planting, 50 mm of water was applied to the plots for seed germination. Each of the plots was randomly assigned to one of three soil water depletion level treatments, with six replications per treatment. Flood irrigation was applied to the plots when the AZSCHED program predicted the soil water depletion of the active root zone had reached the targeted level. The targeted depletion levels of the treatments were 40, 50, and 60%. The estimated irrigation efficiency was assumed at 95% for all treatments. After crop establishment, seven, five, and four irrigations were given to the 40, 50, and 60% depletion treatments, respectively, representing a total water application of 505, 480, and 460 mm, respectively. Rainfall during the season totaled 149 mm, most of which occurred during October 1994, through early January 1995. All plots were given two applications of nitrogen fertilizer (in mid-February and in mid-April 1995) at a rate of 56 and 67 kg-N per ha for the first and second applications, respectively.

During the season, soil water contents were measured with neutron scattering equipment and time domain reflectometry in the plots, before and after irrigations. On June 9, 1995, 22.5 $m^2$ of area was harvested by a combine in each plot. The harvested seed was then cleaned and weighed. The oil content of the seed is currently being analyzed.

**FINDINGS:** Figure 1 shows the crop coefficient curve that was derived for lesquerella from measured data obtained during studies in 1991 through 1994.

Figure 2 shows the soil water depletion of the root zone calculated by AZSCHED during the 1994-95 study between January 1 through May 29, 1995 (DOY 1 through DOY 149), for each of the three soil water depletion levels. From March through early May, irrigation applications were given every 7 to 11, 13 to 17, and 16 to 24 days for the 40, 50, and 60% depletion levels, respectively. Soil water contents measured during the study are currently being analyzed. That data will be used to assess the correlation between the measured and predicted soil water depletion and crop water use during the season.

The 50 and 60% depletion treatments received 96 and 94% of the total water applied given to the 40% depletion treatment, respectively (table 1). All treatments, however, received a total water application above the estimated lesquerella seasonal water requirement of 600 mm.

Analysis of the seed yield data indicated that mean yield for the 50% depletion treatment was significantly higher than that for the 60% depletion treatment at the 0.10 level of probability (table 1). However, the difference in yield between the 40 and 60% depletion level treatments was not significant.

**INTERPRETATION:** Using AZSCHED with the derived crop coefficient could be a useful method for determining the required irrigation application amounts for lesquerella. However, additional analysis is needed to evaluate how well the AZSCHED soil water balance tracked the measured soil water conditions and crop water use during the 1994-95 season. For the soil water holding characteristics at the MAC study site, scheduling irrigations with AZSCHED at 50% soil water depletion (every 13 to 17 days) produced the highest seed yield. That result was consistent with past studies (1991-1994), which, collectively, indicated that the highest seed yields were obtained with irrigations about once every two weeks between late February through May. Yields have generally been depressed when irrigations were given at intervals of three weeks or longer during mid-season.

**FUTURE STUDIES:** Another study is planned for next year during the 1996-97 season to further assess lesquerella irrigation scheduling with AZSCHED.

**COOPERATORS:** J. Nelson, Agronomist, The University of Arizona Maricopa Agricultural Center.

Table 1. Total water applied and seed yield for treatments in 1994-95.

| Soil Water Depletion (%) | Total Water Applied[1] (mm) | Seed Yield[2] (kg/ha) |
|---|---|---|
| 40 | 705 | 1010ab |
| 50 | 680 | 1125b |
| 60 | 660 | 915a |

[1] Includes irrigation and seasonal rainfall.

[2] Seed yield means followed by different letters indicate a statistical difference at the 0.10 probability level.

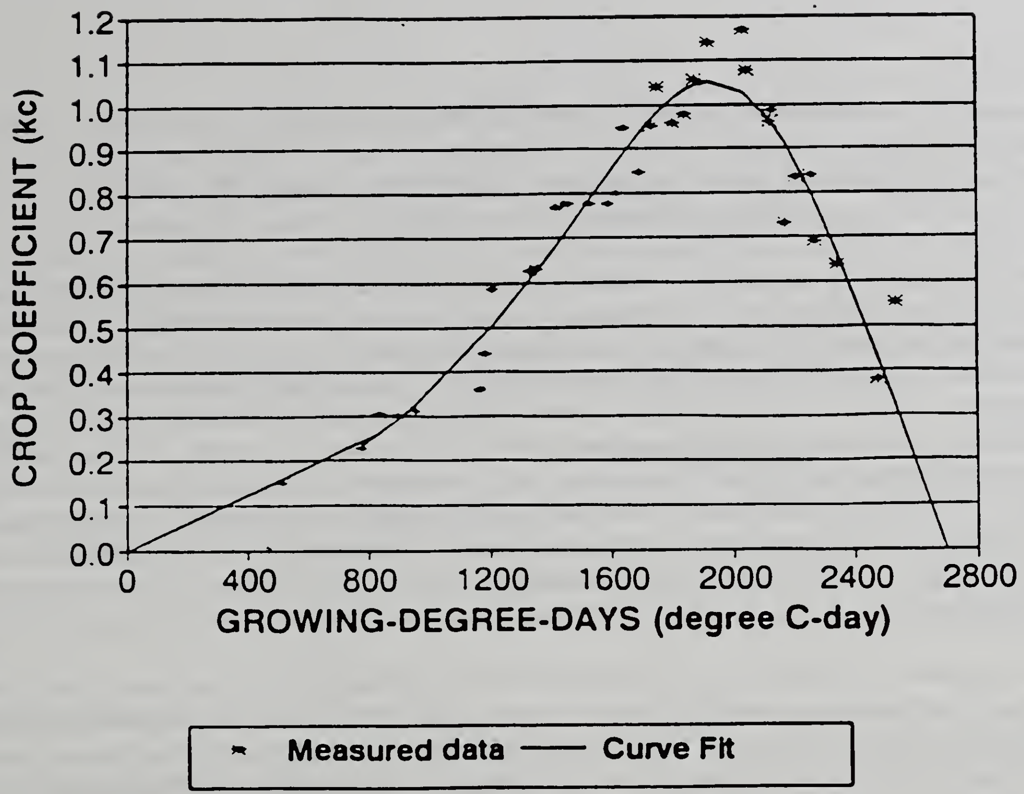


Figure 1. Measured lesquerella crop coefficients ($k_c$) and fitted curve as a function of accumulated growing-degree-days.

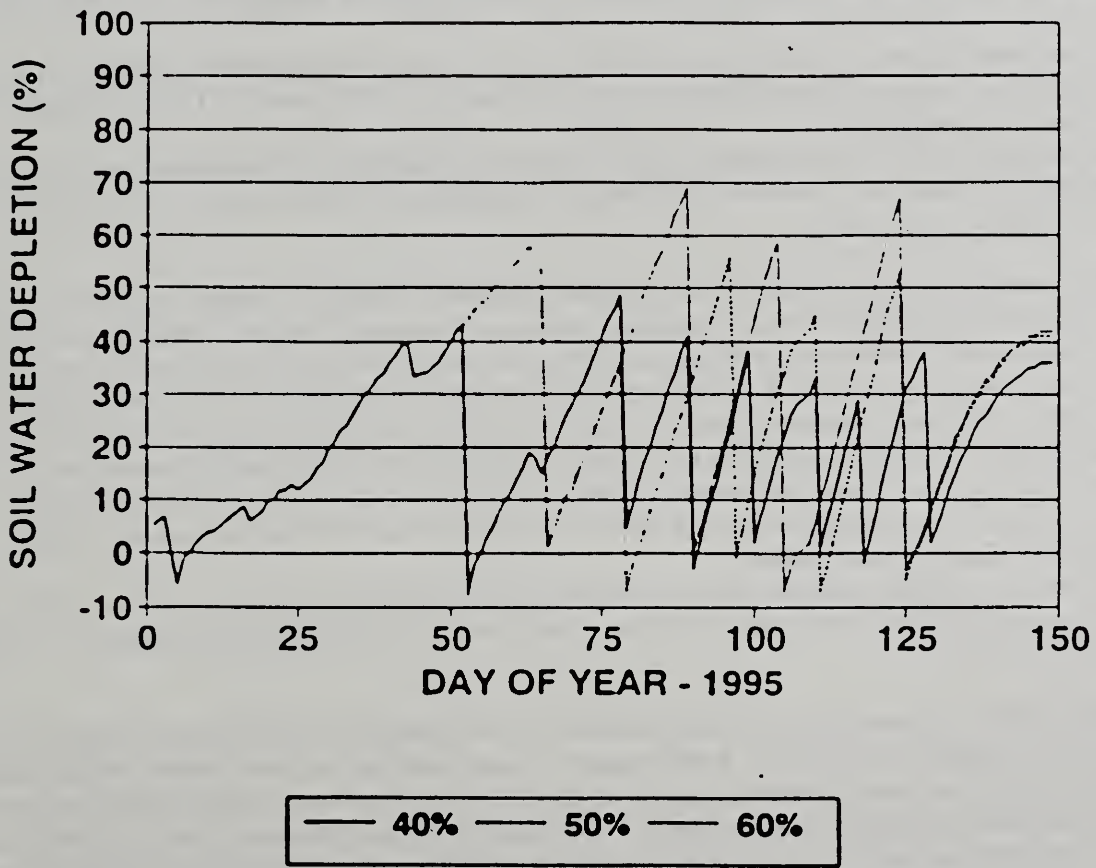


Figure 2. Soil water depletion with time as predicted by the AZSCHED program for the 40, 50, and 60% depletion treatments.

## VERNONIA GERMPLASM IMPROVEMENT

T.A. Coffelt, D.A. Dierig, and A.E. Thompson, (Collaborator) Research Geneticists;
and F.S. Nakayama, Research Chemist

**PROBLEM:** Natural epoxidized oils are potentially important for industrial use as drying agents in reformulated oil-based or alkyd-resin paints. The United States presently manufactures 1230 million liters of these types of paint varnishes annually. Drying agents currently used in them are major air pollutants, releasing volatile organic compounds (VOCs). Use of vernonia oil in these formulations would greatly reduce the VOC pollutants and create some 150,000 ha of an alternative crop for farmers to grow. *Vernonia galamensis* is one of the small number of plants that contain and produce enough epoxidized oil to make it highly promising for commercialization. *V. galamensis* is a native of Africa and flowers and produces seed only under short day conditions. This characteristic prevents successful cultivation of Vernonia within the continental U.S. However, we have successfully utilized an accession, subspecies *galamensis*, variety *petitiana*, that will flower any time of the year, to produce hybrids containing this trait. The objective of this research is to develop high-yielding germplasm adapted to the U.S. through hybridization and selection and to evaluate Vernonia's agronomic potential as a new oilseed crop.

**APPROACH:** Flowering, plant, oil, seed, and yield characteristics of 11 populations developed from hybrids between *Vernonia galamensis* var. *petitiana* (day neutral flowering) and var. *ethiopica* (short-day flowering), and the *petitiana* parent were determined at six locations: Phoenix and Tuscon, Arizona; Medford, Oregon; Ft. Stockton, Texas; Lexington, Kentucky; and Petersburg, Virginia, in 1995. An additional 12 populations were evaluated at Phoenix and Tucson in replicated yield tests and another 12 populations at Phoenix in an unreplicated test. A planting density test was conducted at Tuscon by varying plant spacing within the rows, which were 1 m apart. Plant populations were established at 15,000, 30,000, and 60,000 plants per ha using spacings of 0.15 m, 0.30 m, and 0.60 m, respectively, in an RCB design with four replications.

Various controlled greenhouse crosses and backcrosses were made between hybrids, day-neutral, and short-day flowering varieties to improve flowering and seed traits. Progenies were field planted at USWCL this past summer for evaluation and further selection.

Seed has been sent to ARS, NCAUR, Peoria, Illinois, for fatty acid analysis. NMR equipment has been calibrated for doing in-house total oil analyses. Selections made here and at other locations were increased over the winter at USDA-ARS facility, Isabela, Puerto Rico.

**FINDINGS:** Results from the 1994 Uniform Vernonia Yield Trials were analyzed by location and across the six locations (Medford, Oregon; Ft. Stockton, Texas; Columbia, Missouri; Petersburg, Virginia; Phoenix, Arizona; and Salta, Argentina). Severe whitefly and disease pressure at the Phoenix location resulted in only flowering data being collected at this location. Results showed that locations differed for all traits with Virginia and Missouri higher in yield and Argentina higher in 1000 seed weight and total oil content. The AO399 check had more flowers/plant; 29E-OR2-14 and 66C-1-9 higher yields; 15D-10-12, 29E-OR2-14, and 66C-1-9 larger seed; and 29E-OR2-14 more total oil. There were significant location x entry interactions for number of plants flowering at 81 DAP, yield, and total oil content, indicating variability in stability for these traits among the populations. Results for the 1995 field tests are still being collected, but preliminary data indicate similar findings.

Selections were made within hybrid and backcross populations based on flower head size, seed size, disease and insect resistance, and number of flower heads per plant. These selections were harvested and then planted in a winter nursery at USDA-ARS, Puerto Rico.

**INTERPRETATION:** Hybrid lines have been identified that have nearly the same flowering response as the donor parent of this trait, A0399 var. *petitiana*. A0399 cannot be strictly called a day neutral variety since a response in the amount of flower heads produced is dependent on day length. However, variation was seen within this variety, allowing further selection and backcrossing onto the hybrids. The barrier to growing Vernonia in the U.S. has been overcome through this hybridization, but improvement is still necessary for future commercialization. Significant improvement in the other traits studied also can be made through further selection within these populations. The significant population X environment interactions indicate the importance of evaluating these populations in multiple environments. Lines for commercial production may have to be selected in the environment where they will be grown. The higher seed weights

and total oil contents from Argentina may be due to the fact that only mature flower heads were harvested at this location. This may also account for the lower total yield observed in Argentina compared to the U.S. locations.

Although plants may have flowered earlier in the 0.60-m spacing, toward the end of the season those plants appeared to be the poorest performers. As plants mature the stems become brittle. There seems to be an advantage to space plants closer, possibly to provide support for other plants. The closer spacing may also force flowering on the top and outside canopy, allowing better plant architecture for harvesting.

The comparison of F1 plants to hybrids from later generations for flower head and seed size indicates that some inbreeding depression occurs. The backcross populations have successfully increased the number and size of flower heads per plant. Further improvement should be possible in successive backcross generations.

**FUTURE PLANS:** Financial support from the "Advanced Materials from Renewable Resources Program" from the Department of Defense, through the CSRS, Office of Agricultural Materials, was obtained for a second year (FY95) to support Vernonia research. These funds are being utilized to support faster germplasm increase through the winter nursery in Puerto Rico and cooperative tests at other locations. In Spring, 1996 we will grow-out selections presently being increased in Puerto Rico. These will be evaluated at multiple locations as in this past year. Development of cultural practices for the various locations will be expanded. We also will try to initiate seed dormancy studies on selected lines.

**COOPERATORS:** T. Abbott and B. Phillips, USDA-ARS-NCAUR, Peoria, IL; D.T. Ray and W. Coates, Univ. of Arizona, Tucson; M.A. Foster, TAES, Texas A&M, Ft Stockton, TX; R.J. Roseburg, Oregon State Univ., Medford, OR; D. Hildebrand, Univ. of Kentucky, Lexington, KY; H.L. Bhardwaj, Virginia State Univ., Petersburg, VA; A. Sotomayor-Rios, ARS, Mayaguez, PR; R. Ayerza, Agropecuaria El Valle S.A.

Table 1. Mean vernonia yield, seed weight, and seed oil content of eight hybrid populations and the AO 399 parent from five locations in 1994.

| Line | Yield (kg/ha) | Seed Wt. (g/1000) | Oil (%) |
|---|---|---|---|
| 14D-2-5 | 397 | 2.76 | 37.1 |
| 15D-10-12 | 435 | 3.01 | 38.9 |
| 29E-OR2-14 | 575 | 2.96 | 40.2 |
| 35A-2-9 | 434 | 2.74 | 38.3 |
| 35A-2-10 | 395 | 2.69 | 36.3 |
| 48A-10 | 376 | 2.68 | 38.6 |
| 66C-1-9 | 504 | 3.05 | 37.7 |
| 72A-1-2 | 432 | 2.65 | 36.5 |
| AO 399 | 496 | 2.62 | 38.6 |
| LSD | 115 | 0.13 | 1.4 |

Table 2. Mean vernonia yield, seed weight, and seed oil content of five locations in 1994.

| Location | Yield (kg/ha) | Seed Wt. (g/1000) | Oil (%) |
|---|---|---|---|
| Virginia | 820 | 2.82 | 38.1 |
| Missouri | 325 | 2.76 | 37.2 |
| Texas | 303 | 2.55 | 37.8 |
| Oregon | 645 | 2.53 | 35.2 |
| Argentina | 155 | 3.31 | 41.7 |
| LSD | 86 | 0.10 | 1.0 |

# LABORATORY SUPPORT STAFF

## ELECTRONICS ENGINEERING LABORATORY

D.E. Pettit, Electronics Engineer

The electronics engineering laboratory is staffed by an electronics engineer whose duties include design, development, evaluation, and calibration of electronic prototypes in support of U.S. Water Conservation Laboratory research projects. Other responsibilities include repairing and modifying electronic equipment and advising staff scientists and engineers in the selection, purchase and upgrade of electronic equipment. Following are examples of work orders completed in 1995:

- Design and constructed six interface controller boxes between Batch Controller and Solenoid Valves used in the FACE experiment.
- Constructed four battery charger boxes with batteries and multiple D.C. power distribution boards containing lightning surge protection for use in the FACE experiment.
- Rewired the large valve box to SDM-CD 16 control module for the Campbell CR10 data logger control used in the FACE experiment.
- Designed and constructed the tone generator that is mounted to and used with the minicamera system/frame grabber for the FACE experiment.
- Repaired and modified a variety of equipment throughout the year, including CR21X data loggers and CR7 data loggers, various IRT hand-held guns, polycorders and polycorder cables, the convection oven, the Oxford Nuclear Magnetic Resonance Unit, anemometers, A $CO_2$ controller system, and A $CO_2$-IR analyzer unit.

## COMPUTER FACILITY

T. A. Mills, Computer Specialist

The Computer Facility is staffed by one full-time computer specialist and one computer assistant. Support is provided to all Laboratory and Location Administrative Office computer equipment and applications. The facility is responsible for recommending, purchasing, installing, configuring, upgrading, and maintaining the Laboratory's Local and Wide Area Networks (LAN, WAN), computer systems, and peripherals. The LAN is composed of eight 10Base-T hubs connected to a standard Ethernet backbone providing 96 ports. A local router and a 56kbs lease line to Arizona State University provide a gateway to the Internet WAN. The Laboratory has an Internet Class C IP address and operates under the domain uswcl.ars.ag.gov. Network UNIX services are provided by a Sun micro SPARC 20.

Novell NetWare 3.12 continues to provide most of the network services. The NetWare network consists of a primary file server with six gigabytes of storage, a backup server with two 10-gigabyte tape drives. Remote communications are provided with NetWare Asynchronous Communication Services (NACS) and NetWare Access Services (NACS). E-mail to the Internet is provided through Novell's Mal Handler system (MHS) and an SMTP server.

### Enhancements FY 95

The MHS and SMTP servers were added to provide desktop E-mail to the Internet. Two Microsoft Windows 3.5 NT servers were brought online. One of the NT servers hosts the Laboratory web server (www.uswcl.ars.ag.gov). The NetWare backup server also was added this year.

### Projections for FY 96

The focus this year will be on better remote access to the Laboratory LAN. Better methods for dialing in and out are currently being evaluated. Improved cross-platform integration and resource sharing also will be implemented. New network management and analysis software also will be place in operation.

## LIBRARY AND PUBLICATIONS

L. S. Seay, Publications Clerk

Library and publications functions, performed by one publications clerk, include maintenance of records and files for publications authored by the Laboratory Research Staff, including publications co-authored with outside researchers[1], as well as for holdings of professional journals and other incoming media. Support includes searches for requested publications and materials for the Staff. Library holdings include approximately 1700 volumes in various scientific fields related to agriculture. Holdings of some professional journals extend back to 1959.

The U. S. Water Conservation Laboratory List of Publications, containing about 1900 entries, is maintained on PROCITE, an automated bibliographic program. The automated system provides for sorting and printing selected lists of Laboratory publications and is now accessible on LAN by the Research Staff. Publications lists and most of the publications listed therein are available on request.

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[1] Appendix A lists manuscripts published or formally accepted for publication in 1994 and/or 1995.

## MACHINE SHOP

C.L. Lewis, Machinist

The machine shop, staffed by two full-time machinists, provides facilities to fabricate, assemble, modify, and replace experimental equipment in support of U.S. Water Conservation laboratory research projects. Following are examples of work orders completed in 1995:

- Two free-standing 20-foot spiral staircases were constructed and erected to provide access for data collection at the upper levels of the orange tree chambers. The staircases are fabricated from cold rolled steel and are equipped with drawbridge style walkways connecting the staircases to the chambers.

- Four steady-state canopy gas exchange systems were fabricated for continuous monitoring of carbon and water vapor exchange rates for the FACE experiment. The chambers are 130cm by 100 cm by 75cm, of aluminum frame construction, and have mounting brackets for instrument attachments. The frames are equipped with plexiglass panels 59cm by 100cm with ports and flanges for tubing attachments.

- Twenty chambers were fabricated for soil $CO_2$ flux sampling. The chambers are constructed from 8" diameter schedule 50 PVC tubing. Plexiglass covers with closed-cell neoprene gaskets also were constructed.

- Seventy 30' aluminum irrigation pipes were modified to fit existing irrigation connections. The mating ends of the pipes were cut off, and new connectors were welded into place. Welding repair of tears and holes in the irrigation pipe were done at that time.

- Twelve panels of reflective standard tarp material were constructed for the determination of bidirectional reflectance properties of the material. The panels are made of 2' by 2' 1/4 inch plywood and are painted with a non-reflective flat black paint. The tarp material is attached to the panels with metallic staples placed 1/16 inch from the panel edge.

# APPENDIX A

## APPENDIX A

Manuscripts Published or Accepted for Publication in 1995

1. ADAMSEN, F.J., and R.C. RICE. 1995. Nitrate and water transport as affected by fertilizer and irrigation management. p. 1-4. IN: Proc. Conf. on Clean Water Environment - 21st Century, Vol II: Nutrients. Kansas City, MO. 5-8 March 1995. WCL# 1899.[1]

2. ADAMSEN, F.J., W.J. PARTON, and S.R. BENNETT. 1995. A cuvette design for field and laboratory measurement of water and ammonia flux from soils in a short grass prairie. Comm. in Soil Science and Plant Analysis. 26(5&6):813-830. WCL# 1822.

3. AKIN, D.E., L.L. RIGSBY, G.R. GAMBLE, W.H. MORRISON III, B.A. KIMBALL, P.J. PINTER, JR., G.W. WALL, R.L. GARCIA, and R.L. LAMORTE. 1995. Biodegradation of plant cell walls, wall carbohydrates, and wall aromaticsin wheat grown in ambient or enriched $CO_2$ concentrations. J. Sci. Food Agric. 67:399-406. WCL# 1827.

4. ALLEN, R.G., G.L. DICKEY, J.L. WRIGHT, J.F. STONE, and D.J. HUNSAKER. 1993. Error analysis of bulk density measurements for neutron gauge calibration. p. 1120-1127. IN: R.G. Allen and Christopher M.U. Neale (eds.) 1993 Nat. Conf. on Irrig. and Drain. Engineering, Management & Irrig. and Drain. System: Integrated Perspectives/ASCE, Park City, UT. 21-23 Jul 1993. WCL# 1762.

5. AKIN. D.E., B.A. KIMBALL, W.R. WINDHAM, P.J. PINTER, JR., G.W. WALL, R.L. GARCIA, R.L. LAMORTE, W.H. MORRISON III. 1995. Effect of free-air $CO_2$ enrichment (FACE) on forage quality of wheat. Animal Feed Sci. & Techn. 53:29-43. WCL# 1838.

6. BAUTISTA, E., A.J. CLEMMENS, and T.S. STRELKOFF. 1995. Inverse computation methods for open-channel flow control. p. 593-597. IN: Proc. First Int. Conf. Water Resources Engineering Division/ASCE, San Antonio, TX. 14-18 Aug. 1995. WCL# 1871.

7. BAUTISTA, E., A.R. DEDRICK, and S.A. RISH. 1995. Integrated resource management for irrigation agriculture: The Demonstration Management Improvement Program. p. 173-174. IN: Proc. Arizona Hydrological Society, 8th Annual Symp., Water Use in Arizona, Tucson, AZ. 14-16 Sep 1995. WCL# 1900.

8. BOUWER, H. 1995. Estimating the ability of the vadose zone to transmit liquids. p. 177-188. IN: L.G. Everett, S.J. Cullen, L.G. Wilson (eds.). Handbook of Vadose Zone Characterization and Monitoring. Lewis Publishers. WCL# 1848.

9. BOUWER, H. 1995. New developments in artificial recharge of groundwater and water reuse. IN: Proc. Biennial Groundwater Conf., San Diego CA. 11-12 Sep 1995. WCL# 1875.

10. BOUWER, H. 1995. Surface water, groundwater, and subflow - legal nexus and the hydrologic connection. Water Resources Research Center, The University of Arizona, Tucson, AZ. Arizona Water Resources. 3(6):7. WCL# 1849.

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[1] The WCL# corresponds to the item number on the USWCL Publication List. Please use the WCL# to request USWCL publications.

11. BOUWER, H. 1995. Past, present, and future of water and wastewater. p. 1-6. IN: R.J. Charbeneau (ed.) Proc. First Int. Conf. Water Resources Engineering Division/ASCE, San Antonio, TX. 14-18- Aug. 1995. WCL# 1889.

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# APPENDIX B

## APPENDIX B

*Agricultural and Forest Meteorology, Volume 77, December 1995*

**Special Issue dedicated to the Workshop on Thermal Remote Sensing held at La Londe les Maures, France, September 20-24, 1993**

**Editor:**
**W. Reifsnyder**
**Guest Editor:**
**M.S. Moran, USDA-ARS U.S. Water Conservation Laboratory, Phoenix AZ**

Moran, M.S., Foreword: Thermal Remote Sensing.

Carlson, T.N., O. Taconet, A. Vidal, R.R. Gillies, A. Olioso, and K. Humes. An overview of the workshop on thermal remote sensing held at La Lode Les Manures, France, September 20-24, 1993.

Norman, J.M. and F. Becker. Terminology in thermal infrared remote sensing of natural surfaces.

Laggard, J.P., Y.H. Kerr, and Y. Brunet. An experimental study of angular effects on surface temperature for various plant canopies and bare soils.

Carlson, T.N., R.R. Gillies, and T.J. Schmugge. An interpretation of methodologies for indirect measurement of soil water content.

Vidal, A. and C. Devaux-Ros. Evaluating forest fire hazard with a Landsat TM derived water stress index.

Wollenweber, G.C. Influence of fine scale vegetation distribution on surface energy partition.

Zhang, L., R. Lemeur, and J.P. Goutorbe. A one-layer resistance model for estimating regional evapotranspiration using remote sensing data.

Norman, J.M., W.P. Kustas, and K.S. Humes. A two-source approach for estimating soil and vegetation energy fluxes from observations of directional radiometric surface temperature.